The Met.Office

Scientific and Technical Review
1999/2000

Putting the customer first

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Putting the customer first

An Executive Agency of the Ministry of Defence

The Met. Office Purpose and Aims Statement

Purpose

To be an effective, modern and efficient national meteorological service for the UK.

Aims

To provide our customers, now and in the future, with the range of services they require, in a timely and effective manner, and at a price they can afford.

To make The Met. Office a source of pride to our staff, our owner, and the public.

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Introduction

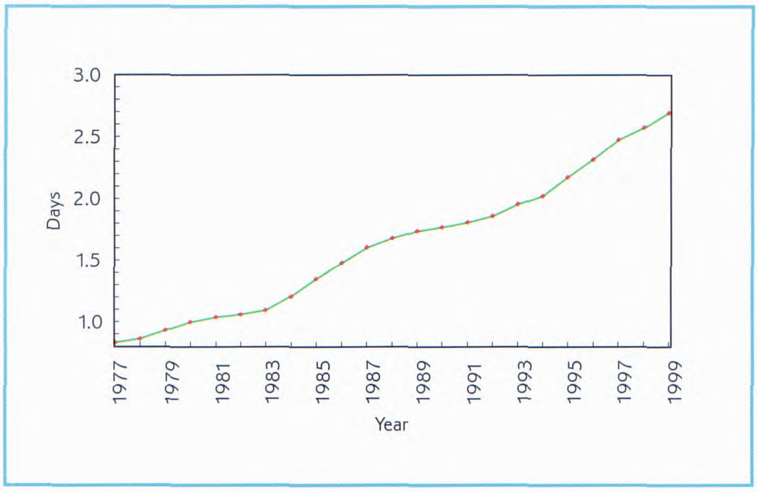
Chief Scientist's introduction

The *Scientific and Technical Review* is a sister publication to the *Annual Report and Accounts 1999/2000.* Here we cover in much greater depth our scientific and technical programmes, and their progress during the year. This is aimed primarily at scientists in other national meteorological services throughout the world, in the academic community and in commercial and research organisations.

This year was the end of a millennium of achievements in meteorology, and this Review will be the last to report on events of the 20th century. If we look back at the science and technology behind our weather forecasts over the last hundred years, we see inventions such as electronic computers, radar and satellites. We also see the automation of some observations and the explosion of global communications. There have been changes in the way weather forecasts are produced and delivered, from ship-to-shore Morse code transmissions, to internet products available via mobile phone.

This progress is set to continue, both in the technology used and the accuracy of the actual weather forecasts. Although, over the years these changes may be imperceptible to the general public, the actual improvement in the statistics decade to decade has been enormous.

This can be demonstrated in the diagram below. This shows a comparative measure of the accuracy of forecasts of atmospheric pressure now with those since 1977. It is expressed as the number of days into the forecast at which the error is equivalent to the one-day forecast error in 1980. In basic terms, we can now forecast the surface pressure out to nearly three days with the same accuracy we had for 24-hour forecasts in 1980. This improvement was expected to level out around about now, but with new developments, the present rate of improvement is continuing and may increase over the next 10–20 years.



INVESTOR IN PEOPLE

Chief Executive's overview

Our performance...

By any measure, 1999/2000 was a successful year for The Met. Office. For the first time, we exceeded both our performance targets for numerical weather prediction (NWP) — measures of our underlying weather forecasting accuracy — reinforcing our position as Europe's leading meteorological service and second to none in the world for accuracy. The global index, in particular, saw an increase of nearly seven points, the biggest one-year rise since the index was introduced 10 years ago.

We also exceeded our targets for efficiency and service quality, demonstrating our ongoing commitment to offer all our customers — from individuals to the largest public and private sector organisations — a better service at lower cost. At the same time we achieved a healthy return on capital employed, ensuring we have the resources to meet our ambitious investment programme and our customers' future needs. And, while we did not achieve our demanding target for commercial financial contribution, our commercial business still helped to reduce the cost of the public weather services, as well as delivering a wide range of quality services to industry and commerce. We also restructured our Commercial Division, putting it on a firm footing for the future, enabling it to compete on level terms in a growing global market.

During the year, we successfully completed several major projects, including the commissioning of our second T3E supercomputer, establishing our new Customer Centre, and managing the year 2000 and leap year (29 February) date changes without a hitch. We also achieved the *Investor in People* standard — a major government target for all public bodies — demonstrating our commitment to our staff and to their development and training.

Finally, in terms of our overall performance, we met nearly 90% of our Business Plan objectives on time, an improvement of some 5% over the previous year.

Of course, none of this could have been achieved without the knowledge, skill and commitment of our staff, and I am pleased to take this opportunity to acknowledge publicly their contribution and to thank them for the indispensable part they have played in our success.

Our services...

While meeting formal performance targets and maintaining our pre-eminent position in meteorology are important, ultimately it is the service we provide to our customers that will determine our success and standing. In particular, it will be our responsiveness to their needs and our ability to add real value to their businesses and to the achievement of their desired outcomes that will set us apart. So, what have we achieved over the past year? In this brief overview I am able to give only a few examples which demonstrate the breadth and depth of our services, and encourage you to read both this report and its sister publication, the *Annual Report and Accounts 1999/2000* to find out more.

As part of our work on climate change, we produced the world's first 100-year prediction of climate, helping planners and policy makers to understand and take account of the changing climate both in the UK and worldwide. At the other end of the spectrum, we issued early and consistently accurate weather forecasts for the eclipse on 11 August (albeit we were unable to improve the cloudy conditions!), and we provided a millennium forecast service to over 700 clients — ranging from the emergency services and hospitals, through central government and local authorities, to the electricity, gas and water companies — to help them plan for the unprecedented millennium celebrations.

Lord Sainsbury (Minister for Science) and Peter Ewins during the former's visit to our NMC and Hadley Centre on 21 January 2000

At short notice, we provided forecasts in support of UK and NATO operations in Kosovo, and for Mozambique in support of humanitarian relief in that flood-stricken country. For civil aviation, we provided detailed information about the ash plume from the eruption of the Hekla volcano in Iceland, helping to ensure aircraft safety and maintain airline schedules; and we equipped the first two British Airways 747s with automated observing software as part of our aviation observing network.

On the international scene, we completed a five-year contract to install a new operational forecasting facility for the Thailand Meteorological Department, helping them to create one of the strongest forecasting capabilities in Asia. Nearer to home, the Scottish storms on the night of 2 January 2000 were well forecast, enabling Scottish Hydro to have engineers in place to speed the repair of downed power lines.

These events show The Met. Office at its best, responding to a wide variety of special events and needs while continuing to provide routine weather forecasts for all our customers 24 hours a day, seven days a week and 52 weeks a year. As Lord Sainsbury, Minister for Science at the DTI, acknowledged when he opened our new Environment Monitoring and Response Centre (EMARC): "The Met. Office continues to provide a crucial service to those affected by the weather every day. This centre I am opening today will respond to extraordinary weather circumstances."

An integrated approach...

The Met. Office is an organisation with tremendous underlying strengths — in the knowledge, experience and sheer professionalism of our staff, in our research and development (R&D) base, in our infrastructure of observations, communications and computing, in our wide range of products and services, and in our understanding of our customers' needs. And it is the harnessing of these strengths into what we call 'know-how' that gives The Met. Office a clear and demonstrable edge over all our competitors.

But, maintaining that edge — to meet the growing demands of our customers, the expectations of the public and the ambitions of our staff — requires sustained and focused effort. And that is why our plans for the next few years are based on steady and sustainable growth, coupled with substantial investment in the training of all our staff; in our infrastructure and underpinning R&D programmes; and in new services which go beyond weather forecasting and climate change into the wider natural environment. At the same time we will maintain our relentless attack on costs to ensure we remain competitive and our services become more affordable.

Throughout the following pages you will see numerous references to our recent activities and to our plans for the future. All these are aimed at achieving our vision of enabling individuals, societies and enterprises everywhere to make the most of the weather and the natural environment.

I hope you enjoy reading our *Scientific and Technical Review 1999/2000*, that you share our vision, and that you will be proud to be associated with The Met. Office and its future.

Observations

Observations of atmospheric and surface conditions are vital for four main purposes. These are to:

- provide input to numerical weather prediction (NWP) and forecasting methods;
- monitor the accuracy of forecasts;
- monitor the weather and provide warning of hazardous conditions;
- determine the variability of climate in space and time.

Observing networks

Network planning

We completed reviews of the UK wind and rainfall observing networks. The resulting policy documents each contain the agreed statement of user requirements for these observations, looking forward 5–10 years, and proposals for cost-effective station network designs.

We initiated a project to explore collaboration with the Environment Agency for the rainfall measurement networks in England and Wales. As well as designing a network to satisfy the joint user requirement for data spacing, frequency and timeliness, the objectives include improving the network management and data exchange arrangements.

We have nearly completed a project to implement more cost-effective solutions to meet the requirement for UK upper-air observations. A mix of solutions is being examined, ranging from radiosondes and aircraft to various innovative remote-sensing tools. To assist with decisions, we carried out NWP impact studies (using radiosonde data from an additional eight stations during three special observing periods each of up to seven days). The results of the EUCOS impact study (see below) will also be highly relevant.

AMDAR and EUCOS

Forecast errors in Europe are in part caused by weaknesses of the current ground-based observing system, particularly in data-sparse areas such as the North Atlantic Ocean. The western European national meteorological services, members of the European Meteorological Network (EUMETNET), have collaborated in a programme to design and implement a EUMETNET Composite Observing System (EUCOS).

First, an impact study was carried out to see if savings can be made by partially replacing the upper-air network over land with automated aircraft data. A number of airlines from the EUMETNET countries participated. For the UK these data are obtained from British Airways aircraft using existing on-board sensors, avionics software and communications. The software package is known as Aircraft Meteorological Data and Reporting (AMDAR), and provides data on ascent, descent and in level flight at a fraction of the cost of the precursor, Aircraft to Satellite Data Relay (ASDAR), and considerably cheaper than traditional methods such as radiosondes. The data are a little less accurate than those from radiosondes and there is currently no viable humidity sensor; however, they are readily available and frequent.

A total of 121 British Airways aircraft have been equipped with the software, which can be activated when required, and the programme has been integrated into the EUMETNET AMDAR system. Seventy-one aircraft were activated as part of the UK contribution to the EUCOS special observing period in Autumn 1999.

During October and November four radiosonde ascents a day were ensured from a selected subset of stations for comparison with aircraft data. We are conducting a series of NWP impact studies to assess the value of increasing the number of AMDAR aircraft reports while reducing the amount of radiosonde data.

Marine upper-air data

The collection of upper-air profile data from ships was resumed when a new Automated Shipboard Aerological Programme (ASAP) system was installed on the container ship *CanMar Pride*. A three-metre container, housing a radiosonde balloon launcher, together with the associated computer systems and antennae, was installed on board by The Met. Office during the first half of 1999 and upper-air soundings began in July. The ship's staff have been trained in the operation of the system, and sonde ascents are normally made at 12-hour intervals throughout the voyage across the North Atlantic, with average sounding heights reaching 22 km. The resultant data are transmitted via the INMARSAT-C satellite communications system to Bracknell for inclusion on the Global Telecommunication System (GTS). Shipborne ASAP systems have been shown to provide a cost-effective source of high-quality in situ profile data which plays a crucial role in forecasting.

Open-ocean buoys

The deployment of a buoy to the north and west of the Shetland Islands (site K7) in June 1999 in support of the offshore oil industry brought the network total to 13, including those operated jointly with Météo-France off the coast of Brittany and in the Bay of Biscay. An acoustic Doppler current meter provided by Fugro Geos was mounted on the buoy to meet a specific oil industry need.

The network was originally intended to consist of ten buoys, and has been extended to a total deployment of 13 without purchasing extra units by streamlining and accelerating the refurbishment of recovered buoys. This allows the whole operation to run on a lower spares holding making more-efficient use of the network assets.

Voluntary observations — severe weather reports

Following a short trial the previous winter, we introduced an extended scheme in November 1999 to obtain additional observations in times of severe weather. This was based on earlier use of our climatological and rainfall networks to provide information for RAF Search and Rescue flights. The scheme, covering Scotland and northern England, is co-ordinated by the offices at Aviemore and Eskdalemuir. So far it has been activated six times during the winter, mainly in periods of significant snowfall. We are reviewing the project in Spring 2000 to assess the value of the scheme and possible development to cover the whole of the UK.

New technology

Automated observing and sub-hourly observation reporting

The requirements for the surface synoptic network and the upper-air network call for significant increases in the temporal resolution of their sampling period in order to capture the majority of the mesoscale signal. A temporal sampling interval of ten minutes and a vertical sampling interval of ten metres have been chosen. This can only be achieved by a network based on automatic instrumentation, and by the adoption of modern telecommunication systems.

We have been operating a Vaisala autosonde (automatic radiosonde launcher) at our Nottingham maintenance centre since March 1998. Two further autosondes were installed in 1999, and are making regular ascents twice per day, one at RAF Woodvale near Crosby, Merseyside, and the other at Eskdalemuir. The latter was deliberately deployed to gauge performance in severe UK winter conditions, but will be moved to Hemsby in March 2000 as part of a forthcoming trial of fully automated observing.

All the manned radiosonde sites are also reliable sources of surface observations, thus the benefits of automation cannot be realised unless both functions are automated. The surface observing system is being upgraded with new Windows NT software and additional sensors. It will operate in fully automatic mode, and will be deployed at Hemsby to support the trial mentioned above. During 2000, further functions will be added (snow depth, surface icing and lightning sensors). The system retains full interactive capability for those sites where a man–machine mix is still required.

Closed-circuit television

Closed-circuit television has the potential to provide valuable additional information for the forecaster when using data from a fully automated observing network. Degradation of image quality occurs as a result of using telephone lines to transmit the data, and a PC-based image-handling system was developed during 1999 which gave the best quality image possible prior to transmission.

We installed cameras at Watnall near Nottingham and Bishopton near Glasgow, in support of a trial by forecasters at Glasgow Weather Centre, which will continue throughout 2000. The Bishopton site is equipped with a visual/infrared pair, and forecasters will develop techniques for extracting maximum benefit from the images.

Further camera installations were initiated in support of a defence forecasting trial involving low-flying (training) areas. All sites involved in both trials will be upgraded with the PC-based system. We also deployed a camera system at the Southampton Oceanographic Centre in support of a Public Met. Service requirement. We plan to build a web site containing high-quality images from all these sites.

Airborne Research Interferometer Evaluation System (ARIES)

An infrared interferometer called ARIES (Airborne Research Interferometer Evaluation System) is being flown on the Met. Research Flight (MRF) C-130 aircraft. ARIES is being used to improve the understanding of the radiative transfer in the thermal infrared region of the electromagnetic spectrum in preparation for IASI (Infrared Atmospheric Sounding Interferometer), a future high-resolution satellite sounder, due to be launched on the METOP satellite in 2003.

High spectral resolution interferometric sounders like IASI have the potential to significantly improve the vertical resolution of temperature and humidity profiling from space and consequently are expected to have a positive impact on NWP.

The MRF C-130 was taken on two detachments in 1999 to study water vapour in the atmosphere. These two detachments called MOTH-Tropic and MOTH-Arctic (Measurement of Tropospheric Humidity) took place in the tropical South Atlantic and the Gulf of Bothnia (Fig.1). During the experiments, we made detailed measurements of the profile of temperature and humidity structure of the troposphere with a range of radiosonde instruments, in situ measurements by the C-130 and dropsondes launched from the C-130 at high level. We are using these data to evaluate the range of radiosonde sensors and to define the atmospheric structure necessary for input into line-by-line radiative transfer models. We then compare the output from these models with radiance spectra observed by the ARIES instrument.

Airborne microwave radiometry

We added three new channels to the Microwave Airborne Radiometer Scanning System (MARSS), centred on the 183.31 GHz water vapour absorption line, similar to the AMSU-B channels used to retrieve humidity profiles. By using MARSS on the MRF C-130, we can validate the required radiative transfer models.

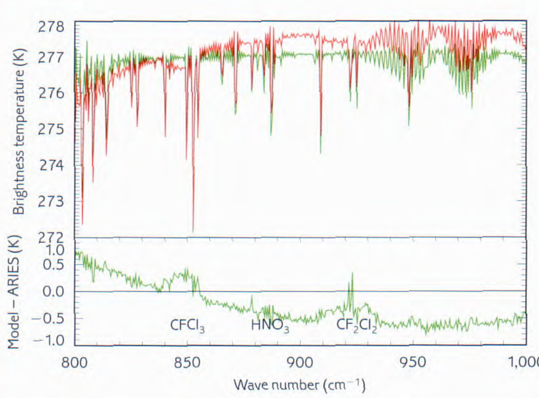


Figure 1. The upper panel shows an ARIES brightness temperature spectrum in red and a modelled spectrum in green. The lower panel shows the difference between the modelled and observed spectra. The ARIES data are from a nadir view at 8 km above the Gulf of Bothnia gathered during the MOTH Arctic experiment. The modelled spectrum was generated using the Laboratoire Météorologie Dynamique's 4A model initialised using the temperature and humidity structure of the atmosphere measured by a dropsonde launched by the MRF C-130 at the same time as the ARIES observations were made.

We operated MARSS on the MOTH experiment to study radiative transfer in a humid tropical atmosphere, near Ascension Island in the South Atlantic during April/May 1999 (Fig. 2), and in a cold, dry atmosphere over the Baltic in December 1999.

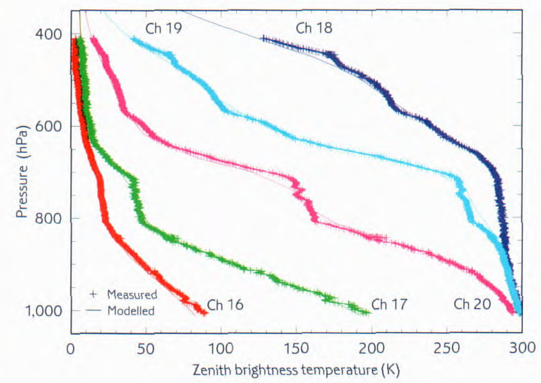


Figure 2. Observations of zenith brightness temperature measured by the MARSS instrument on the C-130 during a profile in the tropical South Atlantic. The measurements are shown as crosses and the model simulations using the Liebe 1989 radiation code are shown as solid lines. The model was initialised with the aircraft-measured temperature and humidity profile.

We conducted radiometric characterisation of the new MARSS channels in our Remote Sensing facility at the Defence Evaluation and Research Agency site at Farnborough, also used to test AMSU-B and other satellite instruments. Results from these tests allow careful calibration and a greater understanding of the data measured on the aircraft.

We operated the microwave radiometers on aircraft over an agricultural area of eastern Germany to measure land-surface emissivity (Fig. 3). These flights were funded under the European Scientific Training and Access to Aircraft for Atmospheric Research Throughout Europe (STAAARTE) programme, for a research group from the Free University of Berlin to validate models of surface scattering and emission.

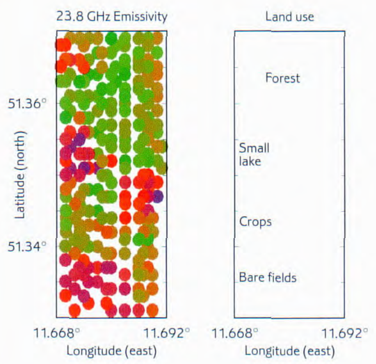


Figure 3. *Emissivity measured by the microwave radiometers on the MRF C-130 at 23.8 GHz over a field site in Germany. The left panel shows the measured emissivity, the centre panel indicates the land-surface type and the right hand panel is the emissivity colour scale.*

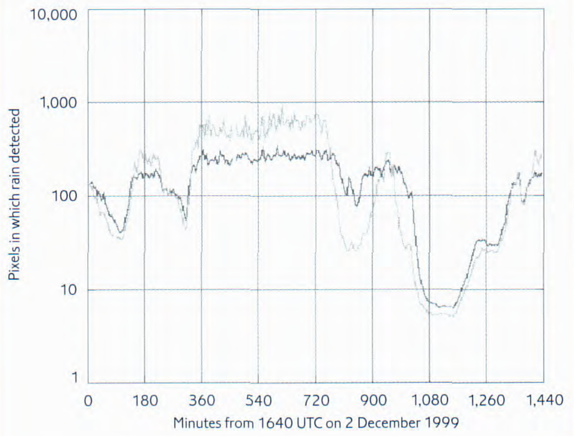


Figure 4. *Rainfall detection. Time-series of the number of radar echoes detected by the new processor at Chenies (grey line) compared to the old (black line). The data are taken from a day when there were four spells of light rain. The new processing provides better discrimination between rain and ground clutter. When rain was falling, a greater area of rain was detected by the new system. At the same time, the baseline number of echoes (due to ground clutter) was reduced.*

Weather radar

New site processor (Cyclops)

We installed a prototype radar data processing system based on a Windows NT/PC platform at the Chenies weather radar, near London (Fig. 4). Both hardware and software were developed in-house, and form the base level system that will be rolled out to other network radars. This is the first phase in the development of a more sophisticated radar signal processing system which will allow for the subsequent inclusion of more recent advances in data handling techniques to improve data and product accuracy.

The increase in on-board processing power has allowed for both greater precision and larger amounts of data analysis at site. It gives potential for much greater resolution in products as well as increased detection sensitivity and accuracy of rainfall amount estimations.

The advantages of increased resolution are well known to data users. The hydrological community has a real need for better spatial resolution for their assessments of run-off for flood warning and control. Current areal resolutions are limited to a global 5 km and a 2 km product close to the radar. The new system will make it possible to access a 1 km product for a large area close to the radar. Figure 5 illustrates the following benefits of the new 1 km data:

- the rainfall-rate distribution is more accurately depicted (the peak rates in the 1 km data are more than twice the peak rates in the 5 km data);
- the areas subject to the highest rainfall rates are more accurately located in the higher-resolution data;
- the 1 km data resolve more of the structure.

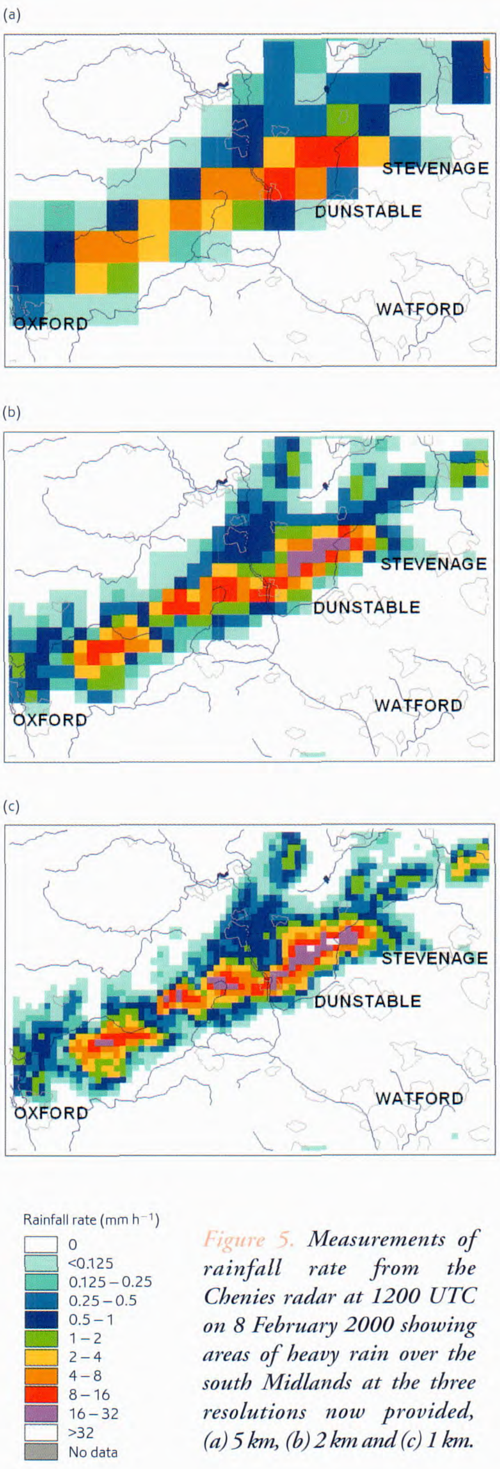


Figure 5. Measurements of rainfall rate from the Chenies radar at 1200 UTC on 8 February 2000 showing areas of heavy rain over the south Midlands at the three resolutions now provided, (a) 5 km, (b) 2 km and (c) 1 km.

Trial of new coaxial magnetrons

Our weather radars employ a cavity magnetron as their source of pulsed microwave energy. The performance of the magnetron depends on its design; the type originally fitted is known as the 'classical' or 'conventional' cavity magnetron. Our experience with this type of magnetron has revealed some major performance shortcomings.

A more modern magnetron design, known as a 'coaxial' magnetron, has many performance advantages over the conventional design. In our application the most important advantages are that it has better frequency stability, and hence we would expect good spectral purity, and also a longer expected lifetime of several years.

We identified a suitable coaxial magnetron and fitted it to the Cobbacombe Doppler weather radar in Devon. Since that time there has been no discernible change in its spectrum. This result is very encouraging and we will fit a second coaxial magnetron shortly, this time to the Chenies radar.

Making the radar data archive accessible

Weather radar raw data are included in a project to create an integrated database that will include both radar (raw and processed) and satellite imagery. The archive/database will be located on The Met. Office's main mass storage system. Once the database is designed, we will further develop the user interface software for the presentation of data to customers. Wider access to the data will be possible by developing a standard archive access forum and through distribution of the data presentation software.

Climate information

During the latter half of the year we set up a centre for climate information. We completed an initial project to place over 100 pages of material on to The Met. Office web site.

The material consisted mainly of maps summarising the weather over the current WMO standard period of 1961–90. Each month, from January 2000 onwards, additional maps and tables are added to The Met. Office web site showing how the recent weather differed from the 1961–90 normals (see Fig. 6 for an example). Work started on more projects to make a wide range of climatological material more widely accessible, by using databases, geographical information systems for presentation and, ultimately, the internet for dissemination. The centre is committed to maintaining the highest standards of data integrity; to that end, we ran a project to assess how best to keep appropriate levels of homogeneity in data series when stations move site.

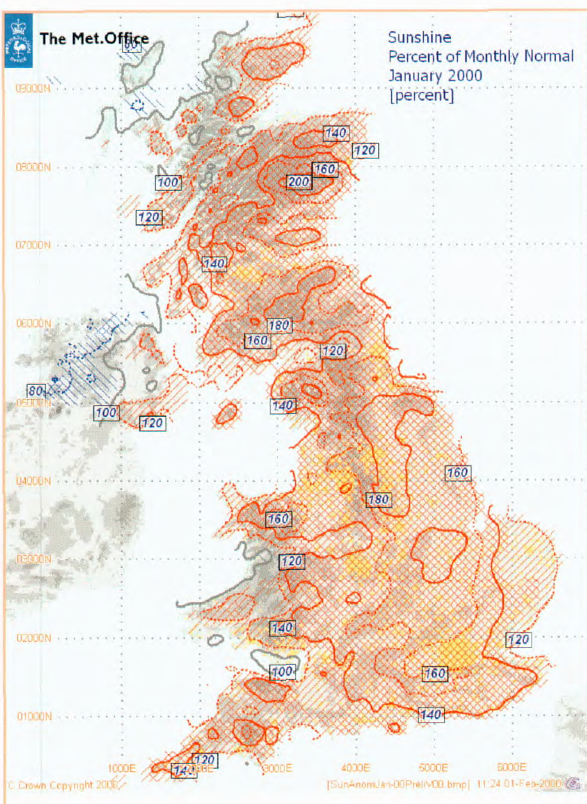


Figure 6. Example of a monthly anomaly map being placed on The Met. Office web site.

Information Technology

Information Technology supports the work of The Met. Office from data collection and processing through to the output of forecasts; from day-to-day office activity to cutting-edge research. The emphasis is on creatively utilising and building on modern technology to provide the most appropriate solutions to our business needs.

Telecommunications

Two-way satellite communications

Since 1995 we have run the Satellite Distribution (SADIS) service on behalf of International Civil Aviation Organization (ICAO). SADIS is a satellite broadcast of aviation data and products, with coverage of Europe, Africa and Asia, and is a component of the World Area Forecast System. ICAO requested an improved two-way capability and Matra Marconi Space, the SADIS prime contractor, designed and implemented an enhanced system. This work was completed in March 2000, creating a platform for future expansion.

New networking solutions

The worldwide 'explosion' in the use of the internet has seen TCP/IP become the de facto standard communication protocol being used today. To take advantage of this and to reduce the cost of 'legacy' systems in The Met. Office based on Decnet communications protocol, we took a strategic decision to migrate from Decnet to TCP/IP-based facilities wherever possible.

We developed alternative TCP/IP-based facilities for file transfer and data translation between the General Purpose Computing Service (GPCS) and HP Unix workstations and all Unix desktop-supported customers now use TCP/IP-based file transfers.

Our wide-area network, Met. Office Remote Sites Network (MORSN), is based on an underlying British Telecom digital network which supports internet protocols. This has continued to expand in association with the roll-out of the forecaster display system to our outstations. This has enabled forecasters to access The Met. Office's intranet. By the end of 2000, MORSN is planned to reach all the forecasting outstations in the UK, and to have absorbed the traffic from some legacy networks.

Improved communications in Europe

The Regional Meteorological Data Communications Network is a new communications network spanning the national meteorological centres of the majority of countries in Europe, plus the European Centre for Medium-range Weather Forecasts (ECMWF). We have been involved in the project from the outset, helping to address both the technical, administrative and political issues of such a collaboration. ECMWF has played a key role in arranging the contract with the supplier, Equant, and in building up to full operational status. The network was accepted into routine service in March 2000 and is being used by The Met. Office to support links to 11 other centres in western Europe.

Modernisation of message switching

Although the main message switch at Bracknell continues to function reliably after many years' service, its proprietary nature and software complexity raise concerns about future viability and cost of support. In May 1999, we approved a business case for replacement by a modern system based on Unix and use of standard software. Following competitive procurement, we placed a contract for a prototype system, to help specify the detailed requirement, in February 2000.

Meteorological databases

We modernised our climatological databases in October 1999 by introducing a system based on relational database technology — Met. Office Integrated Data Archive System (MIDAS). We now have rapid access to about 400 million records of climatological data, in a format that can be 'mined' at will, using off-the-shelf software.

We are replacing our corporate database management system, of which MIDAS and the Central Customer Database are the major applications. This will simplify the users' view of databases, make them easier to use and enhance productivity. This project is on target to complete during April 2000, and will provide a much greater range of facilities both to the user and to the database administrator.

Facilities for our observations database have been extended this year to enable the ingestion of case-study data collected by ECMWF, and to allow the visualisation of observations using the MetView system. We have nearly completed modifications that will increase the ingestion capacity, in advance of major increases in data-volumes expected from the next generation of meteorological satellites.

Central computing facilities

Supercomputer enhancement

Since 1997 our supercomputing requirements have been fulfilled by a Cray T3E machine capable of over 700 Gigaflops. (1 Gigaflop is 1,000 million floating point operations per second.) This is used for numerical weather prediction and climate and environmental research. To keep up with our competitors in these areas, model enhancements were required which meant that we needed to increase our supercomputing capacity. As a result, an additional Cray T3E was installed in 1999. In comparison with the existing T3E, the new machine has 25% fewer processors which run 33% faster. In practice, this increased the overall supercomputing capability by 80%.

Mainframe upgrade

The IBM mainframe general purpose computer (IBM 9672 R45) reached its effective capacity by May 1999. To avoid unacceptable variability in the delivery of products from the operational forecast and reduced service to all other users of the system, we decided in early summer to increase the capacity. By purchasing a smaller version of the same machine (IBM 9672 R25) we avoided issues of compatibility and made savings on the cost of software licences. Installation went very quickly for such a large system. It took three months from the decision to upgrade the system to the system going operational.

The operational forecast suite was moved to the new machine where it can run without being in conflict with any other work. This has led to much improved consistency in timings of output to the forecaster and has released resources on the R45 for use by the rest of The Met. Office.

IT Operations Centre

Development of the systems management software (Tivoli) has continued through the year. We aim to provide a more consistent service to our customers and to reduce the costs of supporting business-critical systems.

Agents installed on each system send system events to the central Tivoli server about their status and any errors that may be taking place. The Tivoli software then processes the information through a number of predefined rules which define the best course of action to be taken, e.g. make an automated response to the event, alert one of the IT Operations Centre staff, or simply store the event for later analysis. The automated responses allow staff to concentrate on aspects of managing the systems where their input will have maximum benefit.

All events received by the Tivoli software help provide the IT Operations Centre with a greater visibility of system performance and an early warning of common problems experienced by our critical systems.

The Tivoli environment is continuously evolving. Over the year a significant amount of effort has been spent on integrating the events from two additional Tandem Message Switches, a second Cray T3E supercomputer and a number of smaller Unix and NT systems for which the staff in the IT Operations Centre have responsibility.

In parallel with the event management development, we have continued to implement the automatic scheduling of production work running on the GPCS using IBM's Operations, Planning and Control (OPC) software. A significant part of the forecast product dissemination is now run under the control of OPC.

MASS storage and archiving facility

Following an extensive procurement exercise, we chose a replacement system for the ageing Grau tape library and associated tape drives and placed a contract with FileTek Inc. This system is called MASS. It comprises an automated tape cartridge library controlled by a dedicated computer. This runs highly specialised software from FileTek to allow users throughout The Met. Office to store, retrieve and manage their data.

The design of the MASS system allows easily scalable extension to store vast amounts of data. Current projections are that we will be storing just under a Petabyte (a thousand Terabytes) of data by 2005.

Systems support

Configuration management (CM)

To improve our software development processes, we have set up a central configuration management (Continuus CM) server. This tool is available for use by small- or medium-sized software development projects, allowing access to a powerful CM tool without the set-up costs. The central server will be used to develop CM plans and services to The Met. Office.

Software testing project

We are running a pilot project for test process improvement throughout The Met. Office, to make further improvements in our software development processes. We want to produce a flexible framework for effective and efficient software testing that can be implemented throughout The Met. Office.

New HR system

During the year, our Human Resources branch procured and installed a new personnel database system. This replaced the previous non-year 2000 compliant database. The new system is a PS-Enterprise system supplied by Rebus Software Ltd. Personal data were transferred to the new system after validation by the staff members to whom it referred. In future, staff will be able to update their own personal particulars via the internal communication network, and managers will have access to generalised reports, statistics and pre-authorised information about their staff. This will increase the efficiency of management by removing the delay inherent in having to request all staff-related information from HR branch.

Rationalisation of system connections

A matrix-switch was brought into service in mid-1999, together with new terminations of the various links to the telecom service suppliers, to enable new and existing systems to be interconnected in a more manageable and flexible configuration. A major motivation for the investment in the matrix-switch and subsequent tidy-up is to achieve a clean state prior to moving operations to a new site.

Year 2000 Project

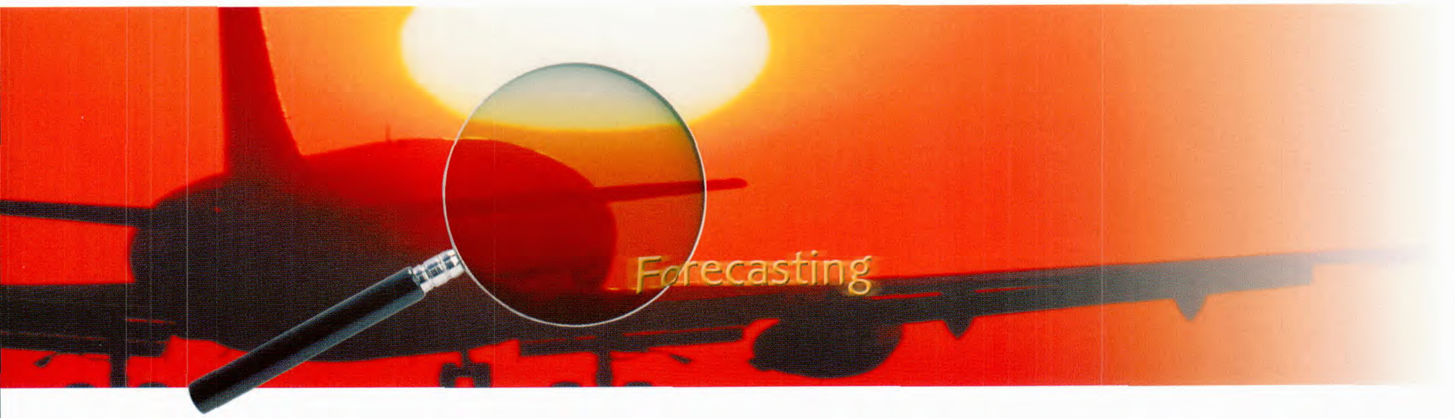
The Met. Office successfully negotiated the millennium roll-over with no effect on the services we provide. As expected, a few minor issues arose, but the Systems Recovery Teams, under the direction of an Executive Management Team, were able to deal quickly with any incidents, so ensuring business continuity. Throughout the millennium weekend reports of our status were provided to our owners, central government and our customers.

All work to check and test our own systems for date errors was completed during the summer with compliance certificates issued by September. The programme was independently assessed by the National Audit Office in September and awarded a blue marking under the Action 2000 traffic light scheme, i.e. no significant risk of material disruption to the National Infrastructure.

During 1999, national preparations for the millennium made it clear that the weather was likely to be a potentially more significant factor than the millennium bug, and if there were any crises, weather could certainly affect the response of the emergency services. To assist authorities and businesses in their planning, a special Millennium Weather Service was set up. Planning information based on climatological averages was provided in mid-year, followed by indications of the likely weather type from the seasonal and month ahead forecast products. In the final run-up, more-detailed 10-day ahead forecasts were provided covering all regions of the country and the major cities, with separate details for upland regions. Reaction to these services from the users was extremely positive.

Improved business continuity

There has been a long-standing requirement to improve our ability to continue to support vital services in the event of a major outage of the IT facilities at Bracknell. As part of the Year 2000 Project preparations, a back-up message switch was brought into service in December 1999 at Headquarters Strike Command, HQSTC. This facility, a smaller version of the main switch at Bracknell, enables us to support the main international data flows, collect and distribute a selection of data to outstations in the UK and communicate with the National Air Traffic Services (NATS). Further development of this facility is planned for 2000/01. Procedures for dealing with an emergency at Bracknell have been reviewed. The Year 2000 Project has given much improved insight into the issue of business continuity generally.



Forecasting

During the year 1999/2000 there has been an increasing emphasis on the achievement of goals in the automation of forecasting. This requires improvements in the basic meteorological forecasts, development of quality control and forecast modification facilities for the use of forecasters, and marketing of the advantages of automated products. In the latter area it has been recognised that real-time automated weather forecasts can form the basis for services in a variety of related disciplines. To make effective use of UK expertise in hydro-meteorology, The Met. Office and the Institute of Hydrology (now the Centre for Ecology and Hydrology at Wallingford (CEH-W)) have jointly set up the Joint Centre for Hydro-Meteorological Research at Wallingford. Staff from our Nowcasting Group have moved to Wallingford to form part of this joint centre.

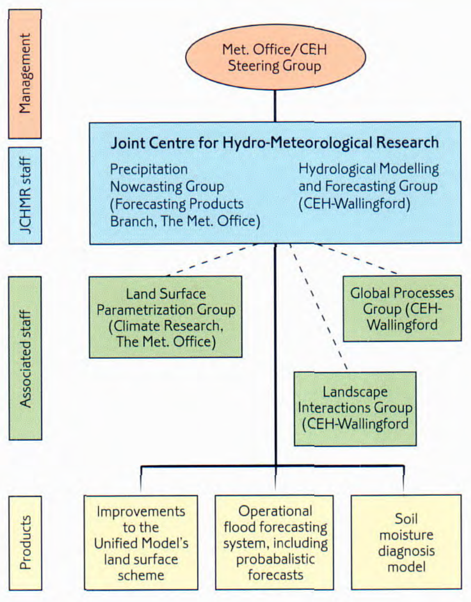


Figure 7. Organisation of the new Joint Centre for Hydro-Meteorological Research at CEH-Wallingford.

Its structure is shown in Fig. 7. Although the focus is on flood prediction, there are several related areas where the centre will assist collaboration.

SITE-SPECIFIC FORECASTING

Forecasting for Specific Sites: System Implementation (FSSSI)

Operational implementation of The Met. Office's site-specific forecasting system was completed during the year. The core of the system is a database currently containing forecasts for some 1,600 locations worldwide.

Short-range forecasts are largely provided by the Site-Specific Forecast Model (SSFM), a single-column version of the Unified Model which predicts local modifications to the low-level atmospheric structure using atmospheric profiles from the 3D NWP models. Figure 8 displays root-mean-square (r.m.s.) errors of screen temperature from different forecast models during December. This shows a significant advantage in using SSFM rather than the mesoscale model throughout the 24-hour forecast, except at midday when all models perform at their best. Note also the large benefit of the mesoscale over the global model.

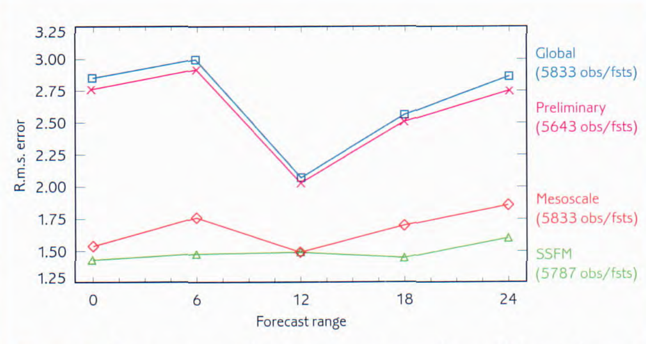


Figure 8. R.m.s. errors of screen temperature from different forecast models (global, preliminary, mesoscale and SSFM) based on the 0000 UTC model runs during December 1999 taken over the 42 sites used in the UK Index.

Longer-range forecasts are provided by a Kalman filter based Model Output Statistics (MOS) scheme. Figure 9 shows the accuracy of maximum and minimum temperatures from the global model MOS. There is a steady increase of the maximum temperature error with forecast range, but the minimum temperature error grows more rapidly at days 5 and 6.

Two product-generation applications have been added to the FSSSI system. The first is The Met. Office's road-surface temperature prediction model

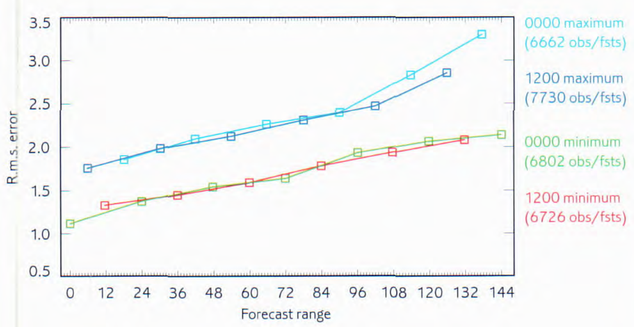


Figure 9. R.m.s. errors of maximum and minimum temperatures from the global model MOS based on 0000 and 1200 UTC model runs during January 2000 and taken over the 42 sites used in the UK Index

which is being run for both UK and overseas sites. The second is a Terminal Aerodrome Forecast (TAF) translator. Comparative verification of the operational and automated TAFs is being undertaken using software developed for the Service Quality Index. Figure 10 shows results for October 1999 to January 2000. The modified Brier score indicates that overall the AutoTAFs perform almost as well as the human forecaster for this sample. However, they miss many more of the poor-weather events. The poorer quality of the AutoTAF forecast near T+0 is partly due to its inability to use observations. Work is under way to enable AutoTAF production to use observational information.

As well as providing guidance to forecasters for use in a variety of services, the FSSSI system is now the source of operational products delivered direct

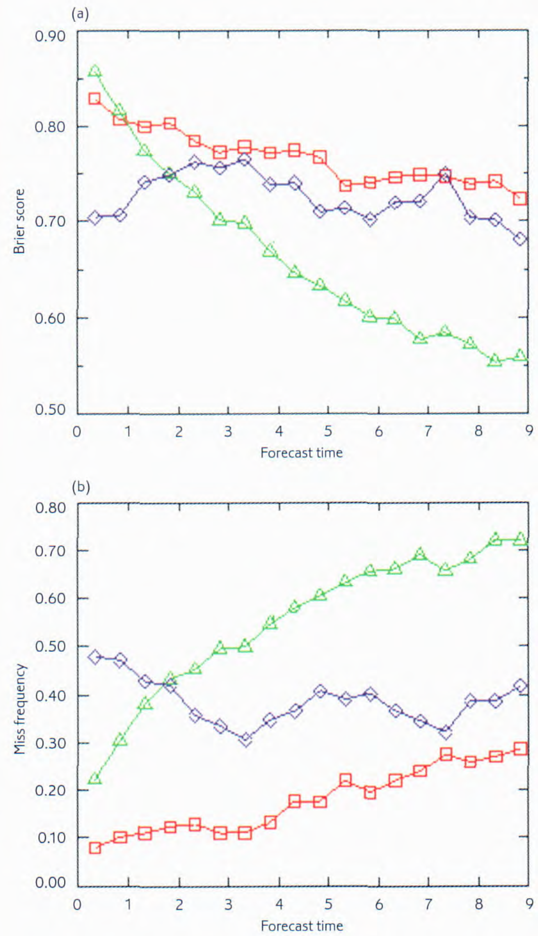


Figure 10. Comparison of manual TAF (red), AutoTAF (purple), and persistence forecasts (green) for predictions of the occurrence of visibility below 5 km at Stansted Airport for October 1999 to January 2000 as a function of forecast lead time. (a) Inverted Brier score (1-2 x Brier Score) and (b) miss rate.

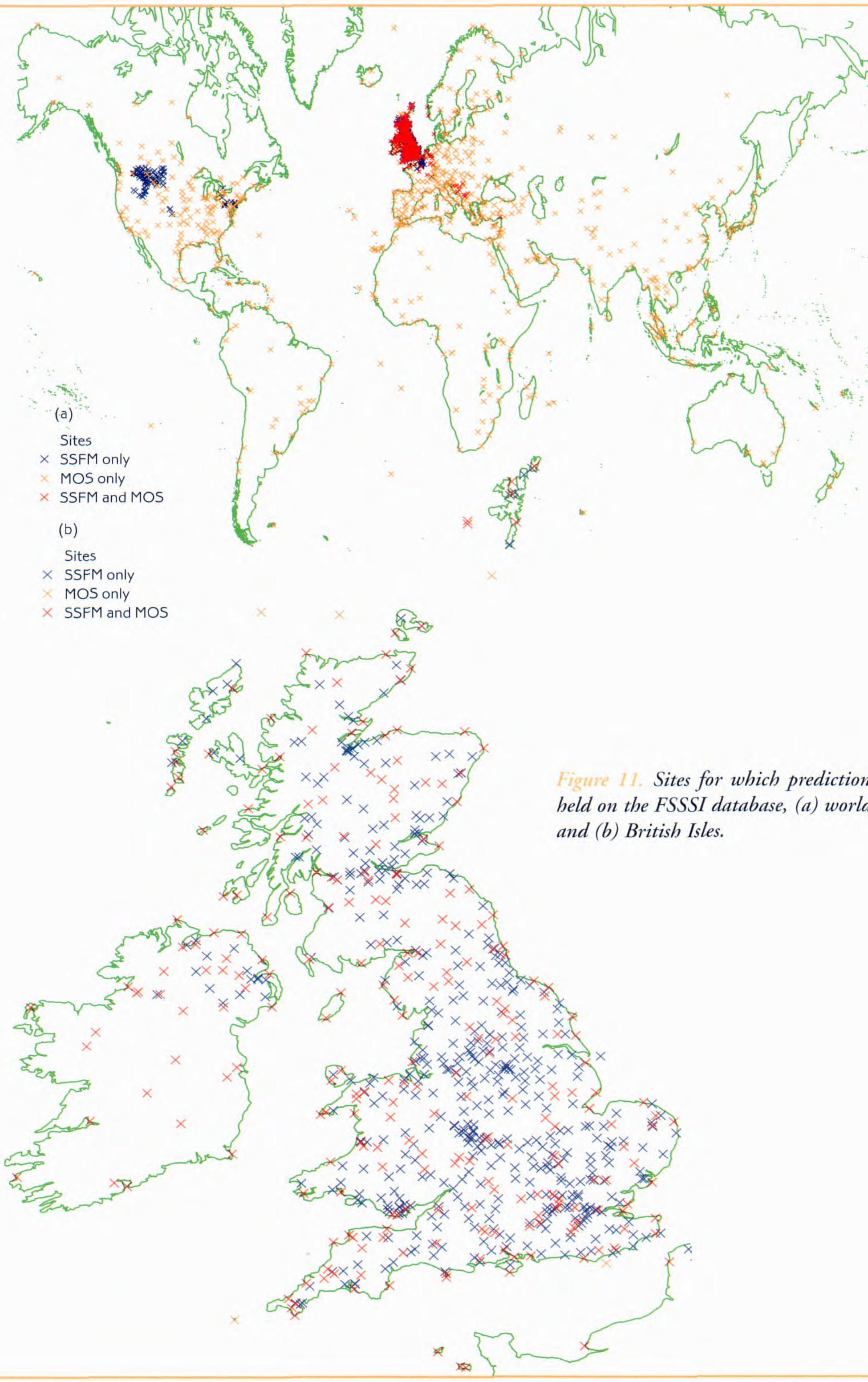


Figure 11. Sites for which predictions are held on the FSSSI database, (a) worldwide and (b) British Isles.

to a number of customers including Reuters, the BBC, and overseas winter maintenance organisations. Figure 11 shows the locations of sites for which data are currently available from the site-specific system.

Medium-range ensemble products

We generate products from the ECMWF Ensemble Prediction System using a Met. Office system called 'Previn'. The focus has been on generating estimates of the probability distributions of screen temperature, 10 m wind speed, and rainfall. Following operational implementation of the system early in the year, we devised a performance index to enable trends in accuracy for sites in the UK to be monitored (Fig. 12). The Ensemble Index is based on the average of scores for temperature, wind speed and rainfall, at lead times of three, five and seven days. The scores are obtained by computing the maximum benefit relative to climatology, at the optimum probability threshold, assuming no cost if the event is neither forecast nor occurs, a cost of one unit when the event is forecast, whether or not it occurs, and a cost of five units if an unforecast event occurs. The result is expressed as a percentage of the score obtainable using a perfect forecast.

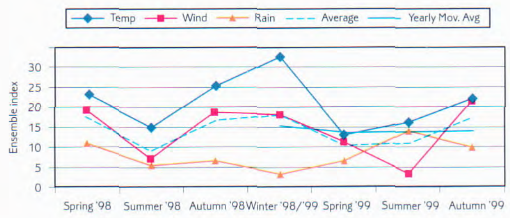


Figure 12. Seasonal time-series of the ensemble performance index for UK sites, Spring 1998 to Autumn 1999.

The temperature score is obtained from an average over the following events.

- Temperature anomaly relative to normal >+2 °C at 1200 UTC
- Temperature anomaly relative to normal >+4 °C at 1200 UTC
- Temperature anomaly relative to normal <–2 °C at 0000 UTC
- Temperature anomaly relative to normal <–4 °C at 0000 UTC

The wind speed score is an average of 0000 UTC and 1200 UTC occurrences of the events:

- Wind speed >Beaufort Force 5
- Wind speed >Beaufort Force 7

The rainfall score is an average of the 0000 UTC and 1200 UTC occurrences of these events.

- Rainfall >0.1 mm
- Rainfall >5 mm

Precipitation and severe-weather forecasting

The primary forecast system for short-range precipitation and severe-weather forecasting in The Met. Office is Nimrod. During the past year, developments have been made to both the range and quality of products.

European radar composite

In collaboration with neighbouring NMSs in Europe, single-site radar data are now being received from several installations in the near continent. These are being integrated into the Nimrod processing system as an extension to the UK radar network. Figure 13 shows a corrected composite image of European radar data. The raw French data are 256 by 256 pixel single-site images at 2 km resolution, covering an area out to 256 km from the radar sites. The Belgian data have a range of 230 km from the radar site, and are also at a resolution of 2 km. These data have been processed using the Nimrod correction scheme (running on 5 km re-gridded data), in which clutter removal has been performed, and then composited into a single image.

High-resolution Nimrod

We are developing a fine-resolution 2 km grid-length upgrade to the current Nimrod forecast, which will incorporate the GANDOLF (Generating Advanced Nowcasts for Deployment in Operational Land-based flood Forecasts) thunderstorm prediction system. During the past year, we made progress in two areas. We set up a 2 km resolution version of the current Nimrod processing software for the southern part of the UK (Fig. 14). In addition, we enhanced the GANDOLF system to use NWP model information to help define the life-cycle characteristics of convective cells.

Overseas performance

We are participating in the World Weather Research Programme (WWRP) Forecasting Demonstration Project (FDP) in Sydney. We are demonstrating and comparing systems for very-short-range forecasting of severe weather using the enhanced observation and monitoring facilities put in place by the Australian Bureau of Meteorology

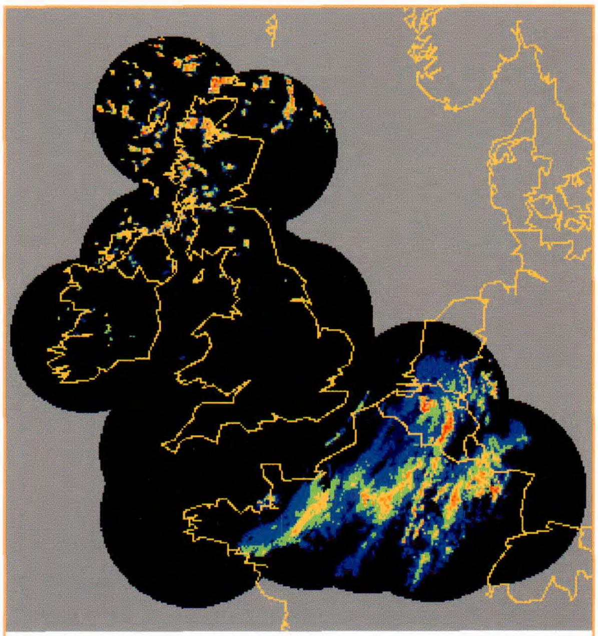
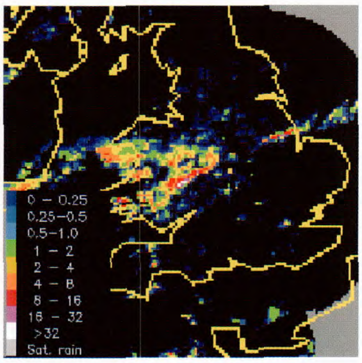


Figure 13. Corrected composite of European radar data for 1600 UTC on 10 February 2000 comprising data from 15 UK radars, six French radars and one Belgian radar.

(a)



(b)

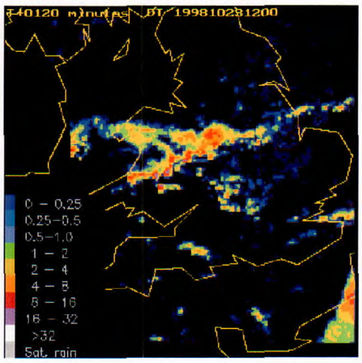


Figure 14. Example of (a) 2 km resolution radar rain-rate composite, and (b) matching two-hour forecast for 1000 UTC on 23 October 1998. Rainfall rates are shown in millimetres per hour.

for the Sydney Olympic Games in September 2000. Both Nimrod and GANDOLF have been implemented using radar and NWP model input data from the Bureau of Meteorology and Fig. 15 shows an example of a forecast from Nimrod.

(a)

(b)

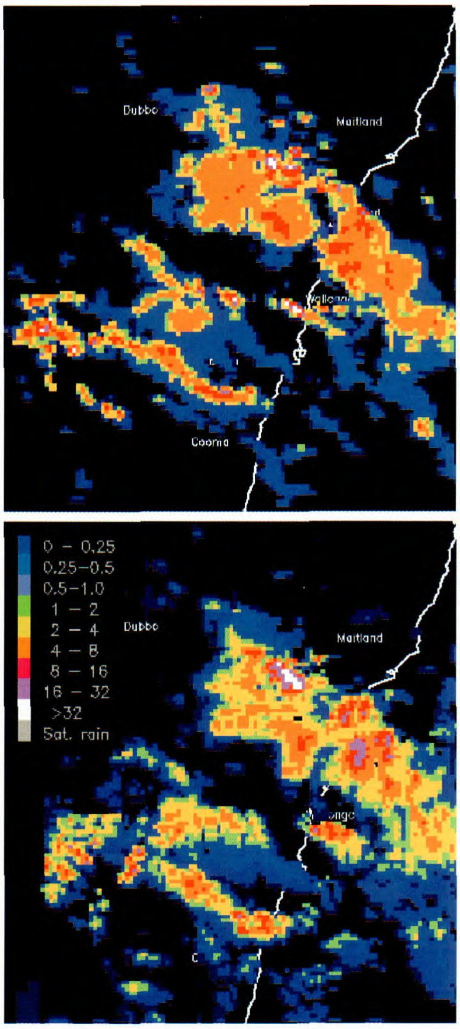


Figure 15. Nimrod rainfall products for Sydney area 0600 UTC on 9 December 1999 from a trial of the WWRP FDP, (a) radar rain-rate observation, and (b) Nimrod one-hour forecast. Rainfall rates are shown in millimetres per hour.

Heavy rainfall warnings

A four-month trial evaluation of automated heavy-rainfall warnings (15 mm or greater in a three-hour period) was undertaken using observations from four areas of the UK covering London, south-west England, north-east England and central Scotland during the period 27 May to

Source of warning information	Hit rate (%)	False-alarm rate as a fraction of issued warnings (%)
Rain-gauge actuals	46	—
Radar actuals	91	39
Nimrod forecasts, 0–3 hours	60	42
Nimrod forecasts, 3–6 hours	32	62

Table 1. Success statistics for identification of heavy rain warning situations in four areas of the UK, 27 May 1999 to 30 September 1999.

30 September 1999. We assumed that rain-gauge reports are accurate but limited by spatial distribution and that radar and rain-gauges together identified all warning situations. We obtained the results shown in Table 1. The first two rows show that radar is much more successful at identifying warning situations than rain-gauge reports alone. The lower two rows show that the Nimrod forecasts are useful up to about three hours ahead, but that accuracy falls off quickly with lead time.

Severe-weather impacts

We have developed a model which quantifies the impact of severe weather (wind, rain, snow, ice and fog) on parts of our national infrastructure. The model is based on a Geographical Information System and works down to postcode level. Tests of the model with past events have produced realistic estimates of impact. Trials are under way of its use in conjunction with Met. Office severe-weather warnings, using automated forecasts as input. Figure 16 shows a severe-wind product, using severity indices over land, which are an intermediate step in estimating impact.

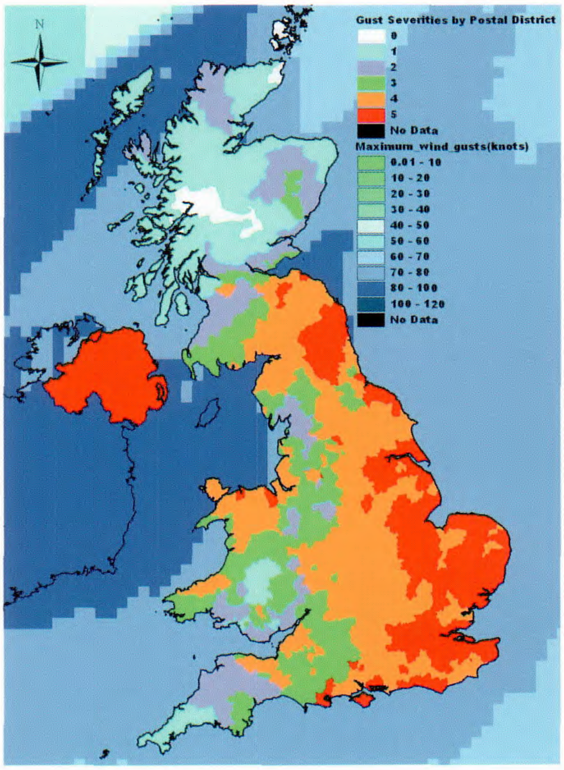


Figure 16. A severe weather impact product. Over the sea, the wind gust is shown in knots, while over land, the impact is indicated by the severity index. Note that different keys are provided for use over land and sea.

Tropical cyclones

Performance of The Met. Office global model in tropical cyclone track prediction has improved markedly in the past year, partly due to improved 'bogusing' techniques introduced in the previous year, and partly due to the improved Unified Model performance following introduction of 3DVAR and the use of ATOVS. Figure 17 shows performance over the past 11 years using a skill index based on the percentage improvement in position forecasts relative to the climatology/persistence (CLIPER) forecasts used as standard by cyclone prediction centres.

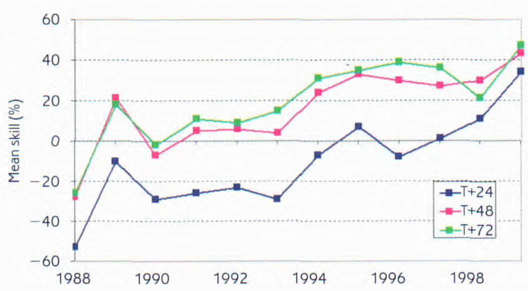


Figure 17. Northern hemisphere tropical cyclone prediction skill relative to CLIPER forecasts, 1988–99.

Andhra Pradesh warning system

In collaboration with Delft Hydraulics of the Netherlands, we started to develop a cyclone hazard mitigation system for the Andhra Pradesh government in India. A PC-based parametric model of cyclone wind and pressure distribution is superimposed on global model wind fields to provide input to the Delft storm-surge model and to wind-damage models. Figure 18 shows a representation of the wind distribution in the Orissa cyclone about 12 hours before landfall, before and after use of the parametric model. Here the parametric model is defined at five times the spatial resolution of the raw NWP model data and increases the peak resolved wind speed from 18 to 58 m s^{-1}. The maximum observed one-minute mean wind speed at landfall was about 70 m s^{-1}.

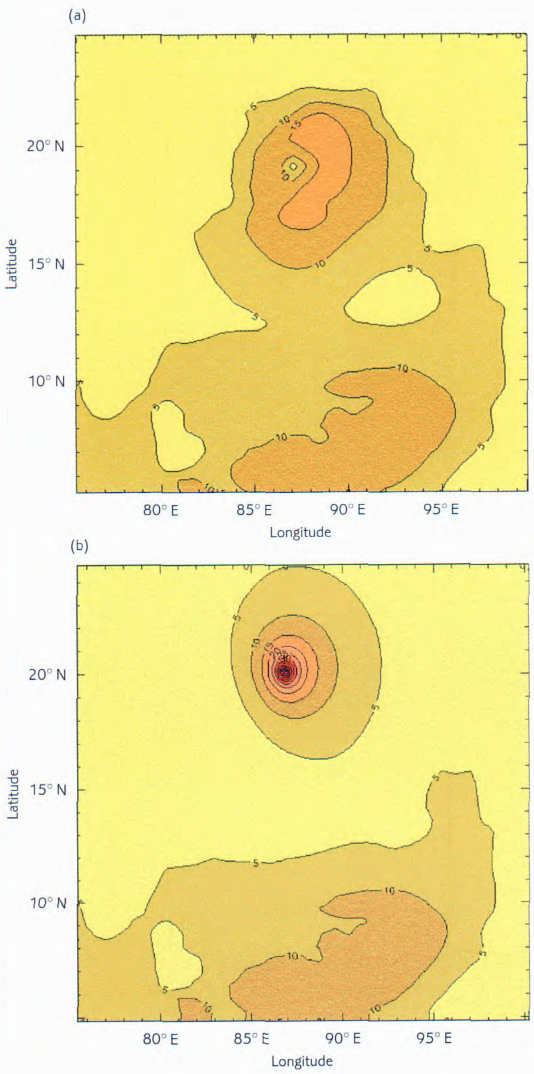


Figure 18. Isotachs at 5 m s^{-1} intervals from a six-hour forecast of the Orissa cyclone for 1800 UTC on 28 October 1999, (a) from The Met. Office global model, and (b) with addition of information from the parametric model.

Nimbus family of production and visualisation systems

Nimbus was designed as a flexible production and visualisation system for use by forecasters and customers. It has well-defined, standard interfaces to enable systems with differing functionality to be built quickly and reliably from basic building blocks. There are currently five configurations: Nimbus, NAMIS, Commercial MIST, Offshore Helicopter MIST and MOMIDS (see Defence).

The system (Fig. 19) is based on the PC platform and comprises a structured-cabled local area network with two Windows NT servers each running NT4, and several dual-screen PCs are also

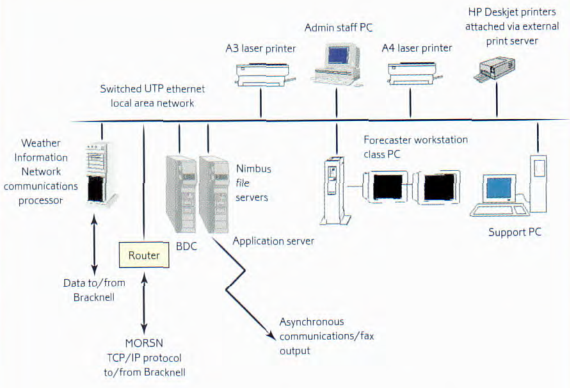


Figure 19. Schematic diagram of a Nimbus installation.

running NT4 to serve the forecaster support and main production platforms. Various lower-specification PCs are used for administration and other work. A dedicated X400 network carries traffic at 64 kbps and generally operates in a broadcast mode supporting data/information transfer between Bracknell and production units. A second British Telecom supplied network called MORSN (Met. Office Remote Sites Network) supports TCP/IP interactive facilities such as the intranet at 200 kbps with potential for much higher speeds.

The software (Fig. 20) provides forecaster support and comprehensive product generation and distribution facilities generally through systems

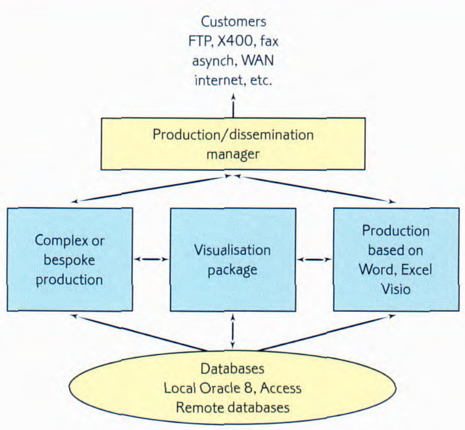


Figure 20. Schematic diagram of the Nimbus software facilities.

in Bracknell via the X400 network. A local fax gateway and asynchronous dial-out communications provide some contingency.

Nimbus is being rolled-out to forecasting and production sites and, by February 2000, had been installed at all Weather Centres, some military sites, BBC and IWP. The modular nature of the Nimbus components enables system design to meet specific objectives and to use various communication methods. Customers and users range from forecasters with local technical support to isolated occasional users with no meteorological or technical knowledge. This successful approach means that the customer base has grown very quickly and support is very important. The visualisation software is included in most of the implementations and currently requires about one person for maintenance and detailed technical support. The complete end-to-end systems require more support, though central IT Operations handles some problems such as data availability.

The database uses Oracle 8 to store data/information. Point data (synoptic data, TAFs, METARs, upper-air data, etc.) are decoded and stored in database tables. Image data and gridded NWP outputs are stored in flat files but are referenced through the database. The user can set up criteria which are checked so that warnings can be displayed automatically.

Visualisation Software is an application written in Borland Delphi which makes full use of the object-oriented programming facilities. It takes data from the Oracle database and offers the user a comprehensive set of facilities for manipulating, visualising, animating, overlaying and windowing the data.

Microsoft Office and Visio are off-the-shelf packages used as the main production tools. Extensive use is made of macros for customised facilities.

Bespoke applications are produced using Visual Basic, for example, to generate products for the media and offshore industries. These applications often include facilities to modify NWP output prior to automated product generation (Fig. 21).

The Production/Dissemination Application is concerned with the organisation and timeliness of product generation and distribution. Written in

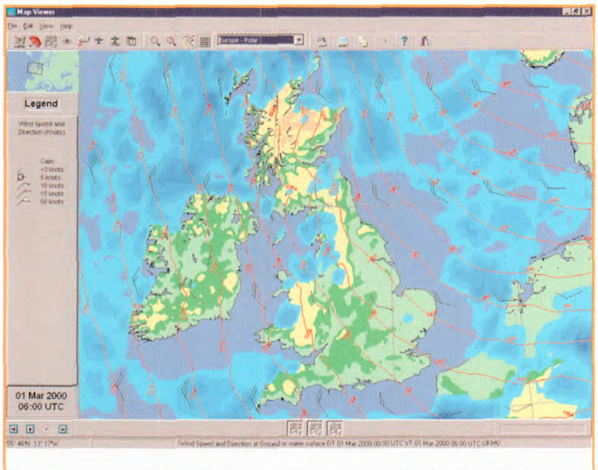


Figure 21. Nimbus map viewer facility displaying cut-out overlays of wind (arrows), pressure (contours) and rainfall (background colours) from a UK area NWP forecast.

Visual Basic, it is an Access database containing information on which product goes where, how and when. It allows timed process initiation and permits both simple and sophisticated production processes enabling fully automated service production where appropriate. Product delivery is comprehensively logged and monitored.

Horace forecasting system

Horace is the forecasting system used by NMC and HQSTC for global and local forecasting at all lead times up to 10 days. It has also been provided to the Royal Navy, the Thailand Meteorological Department, and the United States Air Force in Europe. Major enhancements were implemented during the year including a new cross-section feature, shown in Fig. 22 as part of a full-screen display.

Installation of the Horace system in the Thailand Meteorological Department (TMD) in Bangkok was completed during the year. Figure 23

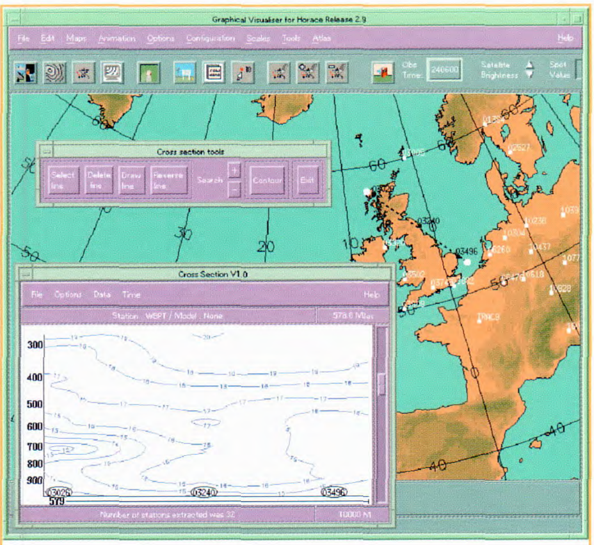


Figure 22. Horace screen shot showing selection and display of a cross section together with tools for manipulating the display.

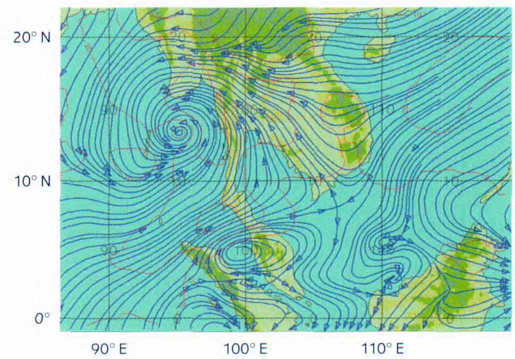


Figure 23. Streamlines (blue) and isotachs (red) at a height of 600 m, displayed to TMD during the early stages of development of the Orissa cyclone.

shows a streamline depiction of winds generated by the on-screen analysis feature during the early stages of cyclone 05B which later devastated the coast of Orissa in India.

The introduction of forecast automation software on Horace has been accompanied by systems to measure the value added by the forecasters. The statistics indicate that, in general, forecasters are improving on the basic model output.

Production of surface pressure forecasts for use by pilots in setting altimeters (QNHs) is now based on the on-screen analysis (OSA) feature applied to the surface pressure distribution near the UK. Figure 24 compares the quality of automated and manual QNH forecasts for January to December 1999.

Another application that has come into routine use during the year is the on-screen field modification (OSFM) facility for modifying forecasts. This enables the forecaster to generate four-dimensional meteorologically consistent modifications to the NWP evolution by modifying just one field at a selection

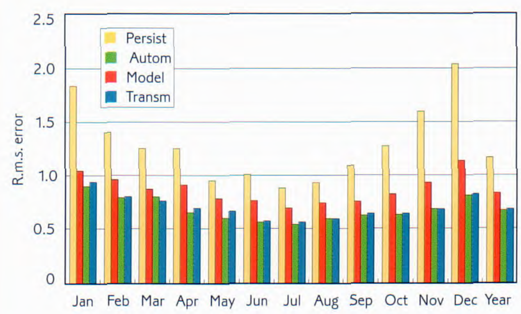


Figure 24. R.m.s. surface pressure errors from QNH forecasts for January to December 1999 from persistence (Persist), raw NWP (Model), on-screen analysis (Autom) and manual modification (Transm).

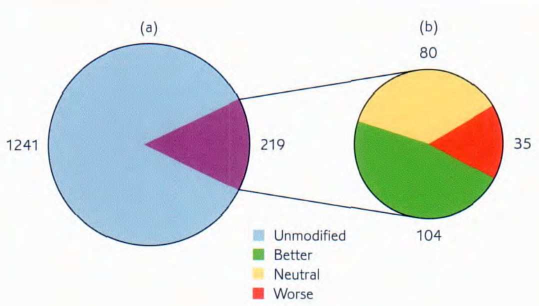


Figure 25. OSFM verification for 1999. (a) Fraction of forecasts modified, and (b) fractions of modified forecasts which improved, reduced and made no change to the forecast accuracy.

of lead times. Figure 25 shows the results of subjective verification of the benefits of this procedure during 1999.

Aviation

A wide variety of meteorological problems of interest to civil aviation was tackled during the year. Amongst these there was an increasing emphasis on meteorological requirements for support of future air traffic regimes capable of absorbing the expected future increases in capacity.

Height monitoring

Work is under way under contract to the EUROCONTROL agency with the aim of reducing the vertical separation of aircraft over Europe. Monitoring is required to establish whether the aircraft altimetry systems are accurate enough to meet the required safety standards. Portable GPS monitoring units (GMUs) will calculate the actual height of aircraft unable to fly over one of the three existing height monitoring units in central Europe. To optimise the use of GMUs the operators need forecasts of significant weather so that they avoid mounting the units on aircraft planning to fly through turbulence, frontal regions or in strong winds. These forecasts have long lead times and there are no associated safety implications so the service will be totally automated and web-based. Figure 26 is an example of a chart produced in this way.

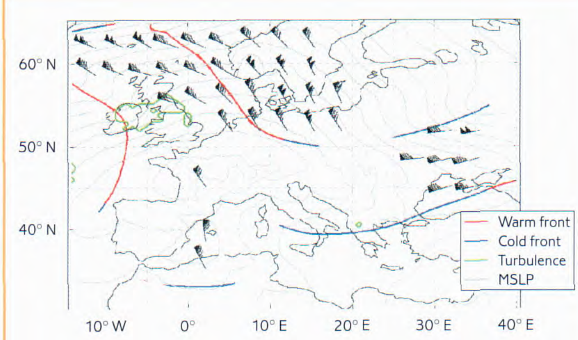


Figure 26. Automated 42-hour forecast of significant weather for 1800 UTC on 3 February 2000, showing mean sea-level pressure contours, areas of strong upper winds (feathered arrows), turbulence and surface fronts.

Analysed heights of the pressure surfaces at which the aircraft should have been flying will be provided to estimate altimeter accuracy. If the operators need additional reassurance as to the accuracy of an analysis then the WAFTAGE

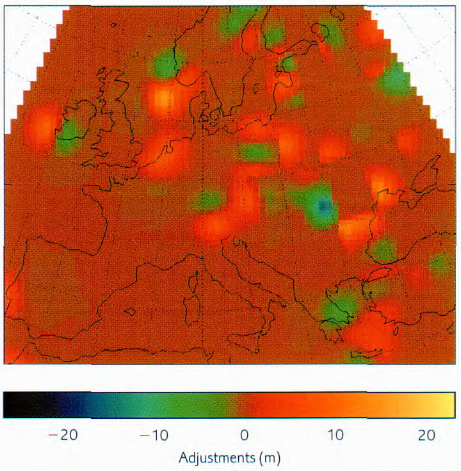


Figure 27. Adjustments made to the NWP analysis using WAFTAGE at 0000 UTC on 6 January 2000.

(Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe) optimal interpolation scheme will be used to nudge the analysis towards observations of height, e.g. radiosonde ascents. Figure 27 shows an example of changes made by WAFTAGE to an analysis at Flight Level 330.

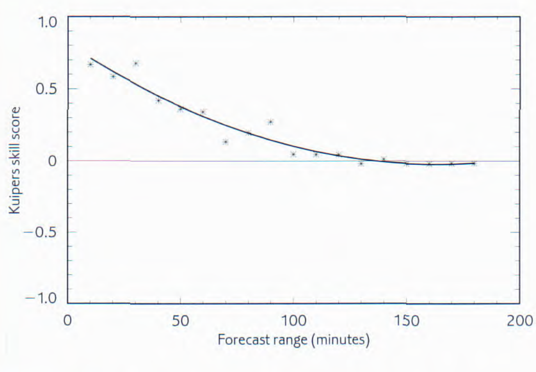


Figure 28. Skill of GANDOLF thunderstorm forecasts compared with upper-beam radar scans for seven events during Summer 1999 as a function of lead time.

Short-range thunderstorm forecasts for the aviation community

We have used upper-beam radar data to verify short-range thunderstorm forecasts produced by the GANDOLF system for seven thunderstorm events occurring in the Summer of 1999. Figure 28 shows the performance of GANDOLF forecasts in terms of the Kuipers Skill Score statistical measure (in this measure, the larger the value the better the forecast). As expected the shorter the range of the forecast, the better it performs. These results were provided to National Air Traffic Services (NATS) so that a decision can be made on whether these forecasts are of use to the aviation community.

Defence

MOMIDS

The Met. Office Military Information Distribution System (MOMIDS) is a member of the Nimbus family of systems providing military users with a web browser interface to a 'local' web server via a fixed leased-line network. A typical local web server would be at the met. office on a military airfield with the clients scattered around the airfield. PCs installed in squadrons and

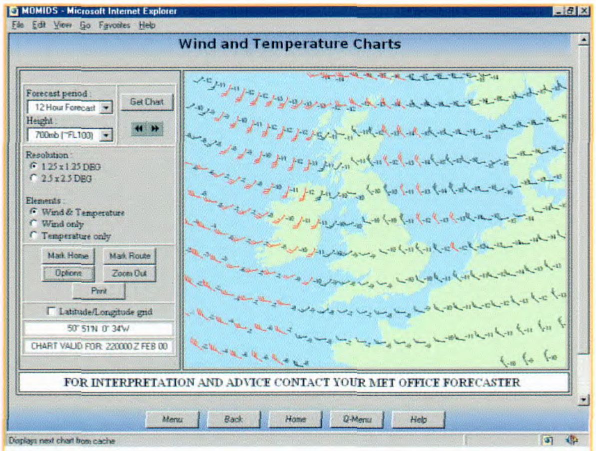


Figure 29. Screen shot of a 700 hPa forecast wind and temperature display from MOMIDS.

operations rooms give users access to a range of meteorological data using standard web-browsing tools (Fig. 29). Also, local forecasters and those elsewhere can inject specific briefing information, either text or graphics, into the system. The installation programme for MOMIDS was completed on time during the year. The display functionality provided by the browser is currently limited. Nimbus technology is being deployed to the met. offices on airfields and work is in hand to integrate the MOMIDS web server into one of the Nimbus servers, to use the Oracle database and enhance the functionality of the web-browser interface to provide facilities approaching that of the full visualisation software. To improve response times and allow more integration into other military systems it has been agreed that MOMIDS should use the RAF's on-base network and a trial has been successfully undertaken at RAF Northolt. Plans are advanced to move to local networks wherever possible.

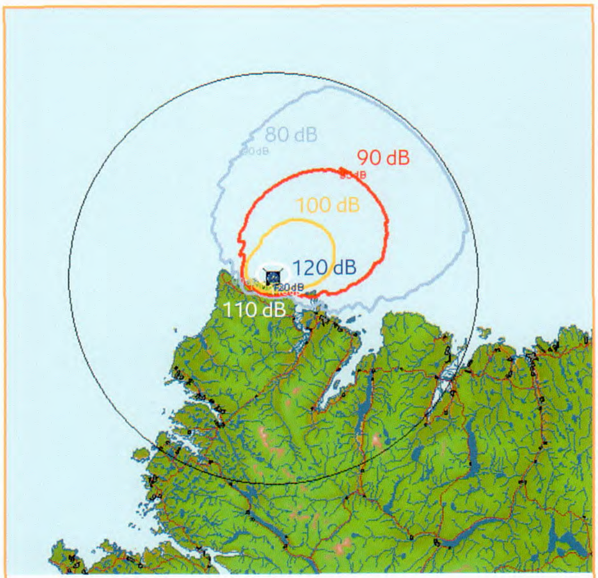


Figure 30. Example of noise distribution (dB) from a source on Garvie Island, northern Scotland.

MONET

Acoustic prediction models, used by Met. Office forecasters at MoD Ranges, predict the propagation of explosive noise in order to minimise noise nuisance that disturbs the local public and causes structural damage to buildings. MONET (Met. Office Noise Evaluation Tool), a new acoustic model developed with Cambridge University, was released at the end of 1999/2000. MONET is a parabolic equation model which has the advantage over the old Ray Tracing Acoustic Model of being able to take account of topography (Fig. 30).

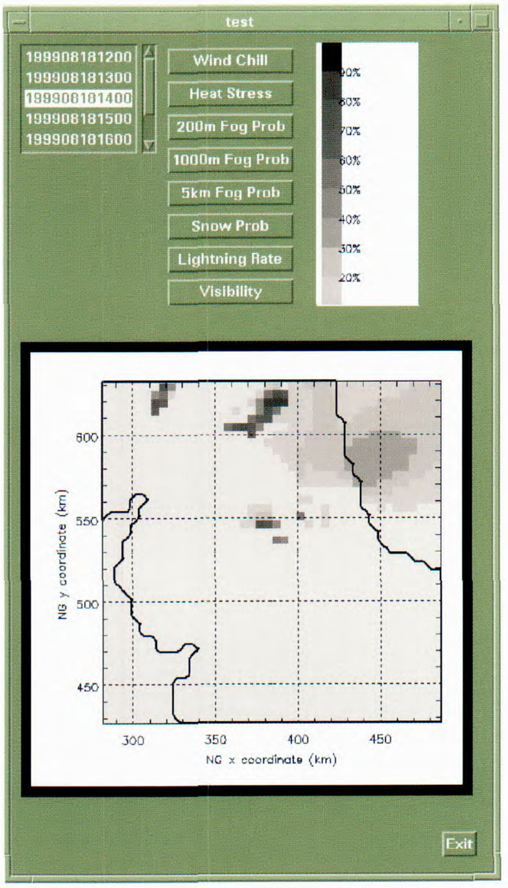


Figure 31. Screen shot of CMETS severe weather facility, showing fog probability.

Additional benefits of MONET come from representation of turbulence, differing terrain reflection coefficients over varying land surfaces (e.g. trees, vegetation) and the input of range-dependent meteorology.

CMETS

Work continued on the CMETS (Computerised Met. System) demonstrator of the use of meteorology in support of the Army. The system consists of a number of automated tools for adjusting large-scale NWP fields to local conditions, together with a range of tools to enable the military commander to access and use the meteorological information (Fig. 31). Amongst these are facilities for displaying the location of weather conditions which exceed specified thresholds.

Horatio

A major project to enhance Horace (see above) for ocean prediction use by the Royal Navy has completed. Among the many products developed in the project was a map of ambient noise levels in the ocean at different frequencies (Fig. 32).

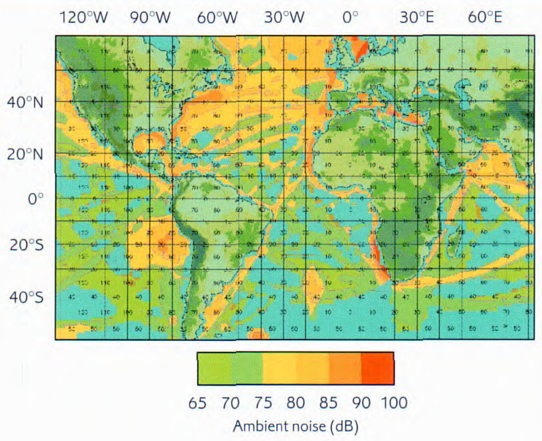


Figure 32. Horatio estimate of ambient noise (dB) at 50 Hz for 0000 UTC on 11 February 2000 in the global ocean.

Numerical Weather Prediction

Numerical weather prediction (NWP) forms the basis of nearly all of the forecasting services provided by The Met. Office, ranging from UK weather predictions for a few hours ahead to experimental seasonal forecasts for the whole globe. The numerical models used to produce these forecasts are developed within the Unified Model (UM) system, which provides the computational and scientific framework necessary for both climate prediction and NWP. We maintain and routinely run global and regional versions of the UM in the operational suite of computer programs. In addition to its use for operational short-range forecasts, both globally and in a high-resolution 'mesoscale' configuration over the UK, we also use the UM for monthly probabilistic forecasts made on behalf of specific customer groups, and for experimental seasonal forecasts.

The UM computer code is available for use by UK universities and international research institutes. The sharing of code in this way has led to increased co-operation and synergy over a range of NWP-related applications, leading to feedback on performance and the development of new techniques for modelling the atmosphere. Closer interaction with UK universities occurs via the Joint Centre for Mesoscale Meteorology (JCMM), which is run jointly by The Met. Office and the Department of Meteorology, University of Reading.

Our ability to improve the accuracy of weather forecasts depends crucially on how well we utilise observational data, and in particular new data sources, to create the best initial conditions for a forecast. A new technique for incorporating observational data into the model, known as three-dimensional variational analysis (3DVAR), has been under development for a number of years and was brought into operation in March 1999. The variational analysis algorithm offers considerable scope for further development, especially in the assimilation of many types of satellite data. This capability was exploited immediately with the simultaneous operational introduction of observational data from the Advanced TIROS Operational Vertical Sounder (ATOVS) instruments on the NOAA-15 polar-orbiting satellite.

Measuring the success of our weather forecasts is also an important part of the process of improving NWP. Research is under way to derive alternative verification measures to the traditional root-mean-square (r.m.s.) errors, in order to provide more-detailed information on regime-dependent model errors and how well we predict extreme events. This will not only allow us to better understand the causes of model error, but will provide customers with NWP performance measures that relate more closely to the impact of the weather on their day-to-day business. An example of this type of approach is illustrated in Fig. 37.

OPERATIONAL FORECASTING MODELS

Enhancements to the global data assimilation and forecasting system

During the past year we have improved the treatment of several different observing systems within the framework of the new 3DVAR data assimilation system. The changes comprised:

- *Better use of ATOVS data — direct assimilation of radiances*

  3DVAR allows us to make better use of observations that are not directly related to model variables. We exploit this by minimising the departures of observed radiances from the calculated model radiances rather than using retrieved profiles of temperature. This direct approach avoids the need to make the rather dubious assumptions that the retrieved temperatures are independent of the model and that the errors at different levels are uncorrelated.

- *Use of new data source from SSMI satellite*
  The Special Sensor Microwave Imager (SSMI) is an instrument flying on the DMSP series of US defence satellites. The microwave system senses the microwave emission from the ocean surface, which is dependent on ocean wind speed. Thus, with an appropriate surface emissivity model and some background information, wind speed can be retrieved.
- *Improved use of surface pressure from SYNOPs*
  Surface pressure information is available as both mean sea-level pressure (MSLP) and reported station pressure (Pstn), but it is convenient for the assimilation to pre-process the data so they can be compared with the model's surface pressure (Pstar). Mapping MSLP to Pstar is an error-prone procedure because the vertical separation may be large and the Pstn to MSLP calculation done at source may be unknown. For stations below 500 m we have, until now, used MSLP because our knowledge of station heights is often inadequate. By applying appropriate corrections to station heights we are now able to make much more direct use of Pstn.
- *Better use of aircraft data*
  We have reduced the observation errors for the automated aircraft reports (AMDARs) to match those assigned to radiosondes, having determined that their quality is comparable. We have also found benefit from thinning the data volumes to one aircraft per 100 km box per 50 hPa per two hours. As well as being more scientifically correct in that we avoid overweighting the aircraft observations, this protects the operational system against a sudden unexpected increase in observations, which may cause computational problems. The change is most evident over the USA, where observation density is halved, whereas reports from transoceanic flights are unaffected.
- *Better use of scatterometer data*
  Initially we used scatterometer winds at the observed resolution (25 km). This oversampling effectively overweights the data, in particular relative to other components of the surface- and low-level wind observing system. We have benefited both from reducing the number of reports used in the assimilation and from improving quality control.
- *Improved specification of model errors*
  The model error covariance model has been revised to provide shorter vertical scales, better positioning of mid-latitude wind variance maxima and smoother spreading of observational increments in the stratosphere. The statistics used to specify these model errors were also updated to cater for changes in the forecast model's error characteristics as the formulation evolved.

Each component of the change was tested individually before being accepted for inclusion in the operational system. Figure 33 shows the relative benefits obtained from each component using verification statistics for a range of forecast timescales and geographical areas. The single statistic does not of course tell the whole story. We noticed that some changes were much more important in the northern hemisphere winter, in particular the changes to the model error specification and the better use of SYNOPs, whilst the satellite changes had relatively little impact in the northern hemisphere but huge impact in the southern hemisphere.

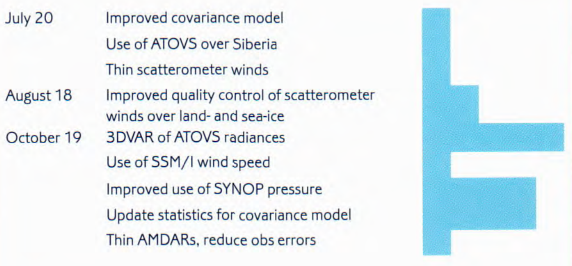


Figure 33. Relative benefits of each data assimilation improvement.

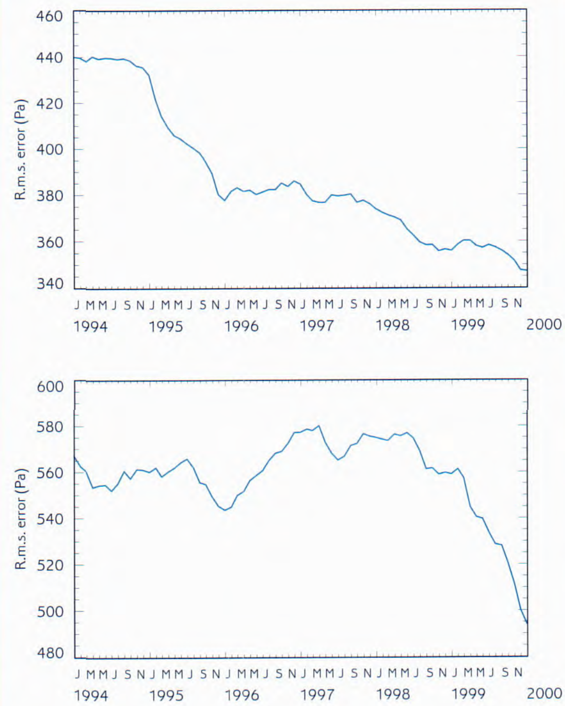


Figure 34. Annual running mean r.m.s. errors (Pa) for day 3 mean sea-level pressure in the northern hemisphere (top panel) and southern hemisphere (bottom panel).

Figure 34 measures the impact of all operational changes since March 1999 following the introduction of 3DVAR. In the northern hemisphere there was a 4% reduction in r.m.s. errors in day 3 mean sea-level pressure forecasts between March 1999 and January 2000 (Fig. 34, top panel). In the southern hemisphere the same changes led to a dramatic 12% reduction in the r.m.s. errors (Fig. 34, bottom panel).

Tropical forecasts have also improved in the last year with a reduction in the positional errors of tropical cyclones for both Atlantic and southern hemisphere domains. For example, in 1998/99 southern hemisphere three-day forecasts were as accurate as the typical two-day forecasts five years ago. These improvements come from better initial conditions for the forecasts (3DVAR, ATOVS) and improvements to the tropical cyclone initialisation technique. Improved model formulation also contributes, such as the change in Autumn 1998 to make the intensity of convection dependent upon the convective available potential energy (CAPE). An example of a good tropical cyclone forecast was Hurricane Floyd, which threatened the eastern coast of the USA in September 1999. The track of this forecast was well predicted at four days lead-time with a small error in the position of landfall on 16 September, but a generally good prediction of the development and final intensity of the hurricane (Fig. 35).

UK DATA ASSIMILATION AND FORECASTING SYSTEM ENHANCEMENTS

In May 1999, a new land-surface exchange scheme and a new non-local treatment of boundary-layer turbulent fluxes were introduced into the operational UK mesoscale model. This has led to improved forecasts of near-surface temperatures and winds, better fog and low-cloud forecasts and a more realistic representation of showers. Previously, the mixing of heat and moisture in convectively

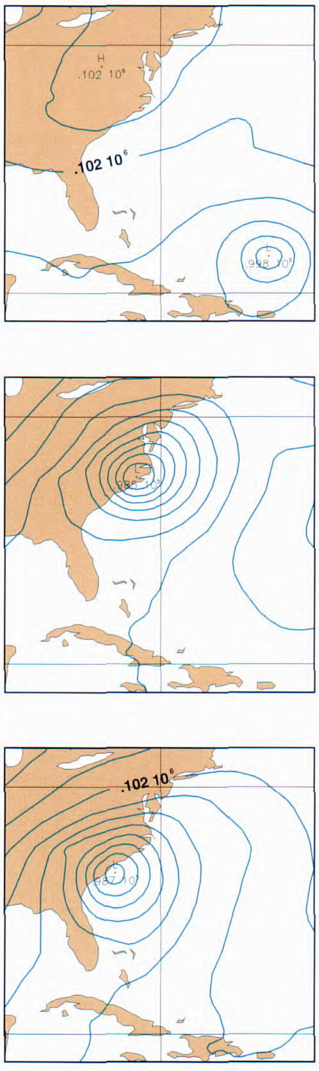


Figure 35. Forecasts and analyses of Hurricane Floyd. Top panel: analysis used to initialise the four-day forecast at 12 UTC on 12 September 1999. Middle and bottom panels: analysis and four-day forecast of Hurricane Floyd valid at 12 UTC on 16 September 1999.

unstable situations led to an under-prediction of showers. An example of the improved cloud forecasts is shown in Fig. 36, where the previous version of the boundary layer scheme has predicted far too much low cloud behind the frontal passage over the British Isles, while the new scheme correctly predicts convective clouds as shown by the visible satellite image. Figure 37 shows the errors in 10 m wind forecasts stratified according to the observed wind speed. The model tends to over-predict light winds (0–5 kn) and under-predict strong winds. Use of the boundary-layer scheme has led to reduced errors in most wind categories (Fig. 37, top panel) and better predictions of the overall number of events occurring in each wind category (Fig. 37, bottom panel).

The radiation scheme used in the UK mesoscale model was replaced in October 1999 by the

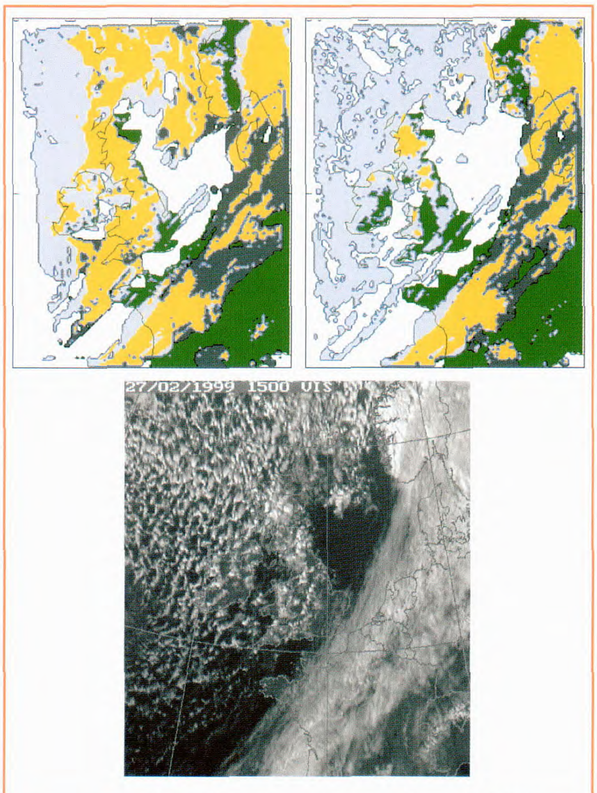


Figure 36. Thirty-three hour forecasts from 06 UTC on 26 February 1999 of low cloud (dark grey) and convective cloud (pale blue), from control (left panel) and the new boundary-layer scheme (right panel); yellow shows where both clouds co-exist. The forecasts used the UK mesoscale model and verify at 15 UTC on 27 February 1999. The bottom panel shows the verifying visible satellite image.

Edwards–Slingo (E–S) scheme. This is a more accurate and flexible code which includes the effects of multiple scattering and is the version used in most other applications of the UM,

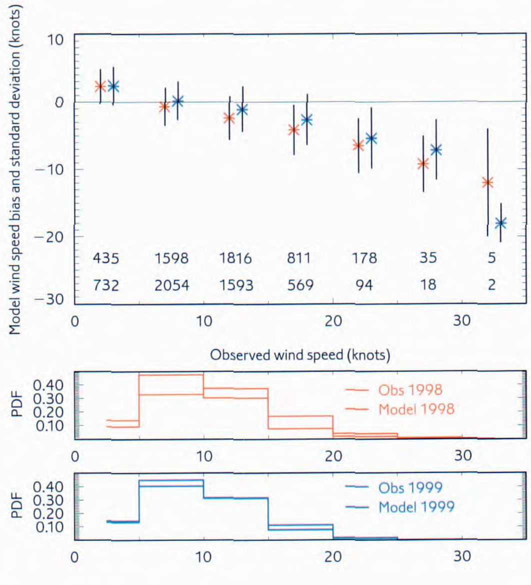


Figure 37. Top panel: mean error (*) and error standard deviation (vertical lines) for the T+24 forecast of 10-metre wind speeds from the UK area model in Summer 1998 and 1999 plotted against observed wind speed (numbers show the observed frequency of events in each wind category). Lower panels: Forecast and observed frequency in each wind category for Summer 1998 and 1999.

including climate simulations. Use of the E–S scheme improves the calculation of surface fluxes in the presence of clouds and leads to much improved forecasts of surface temperatures in cloudy situations, as shown in Fig. 38. The new scheme is computationally more expensive, so full calculations are made at every other grid box and the effects spread to the neighbouring boxes in order to complete the forecasts within the demands of the operational schedules.

3DVAR was introduced into the UK mesoscale model in October 1999. It is used for the analysis of all conventional observations, while a nudging approach is retained for the assimilation of cloud and precipitation data. An advantage of 3DVAR

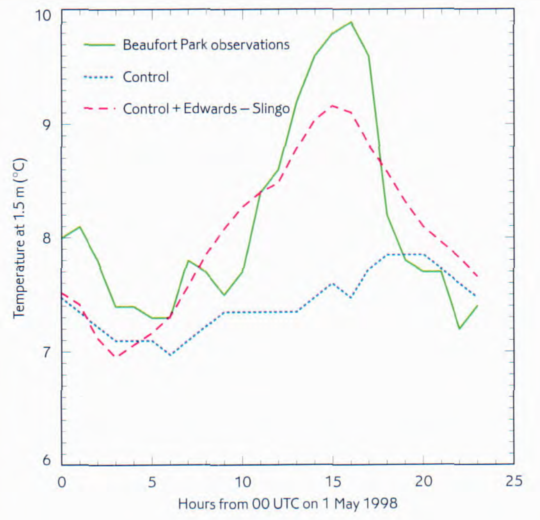


Figure 38. A comparison of UK mesoscale model forecast temperatures for a cloudy day. The plots show the forecast values at a single grid point and are verified against hourly observations from Beaufort Park.

over the previous scheme is that it allows visibility observations to affect the near-surface moisture field as well as the aerosol content. In trials, 3DVAR led to a small overall improvement in key forecast fields, with the main benefits being improved analysis and forecast of fog. Figure 39 illustrates the improvement from 3DVAR in the fog probability output for a case in December 1998 when fog persisted well into the day over a wide area.

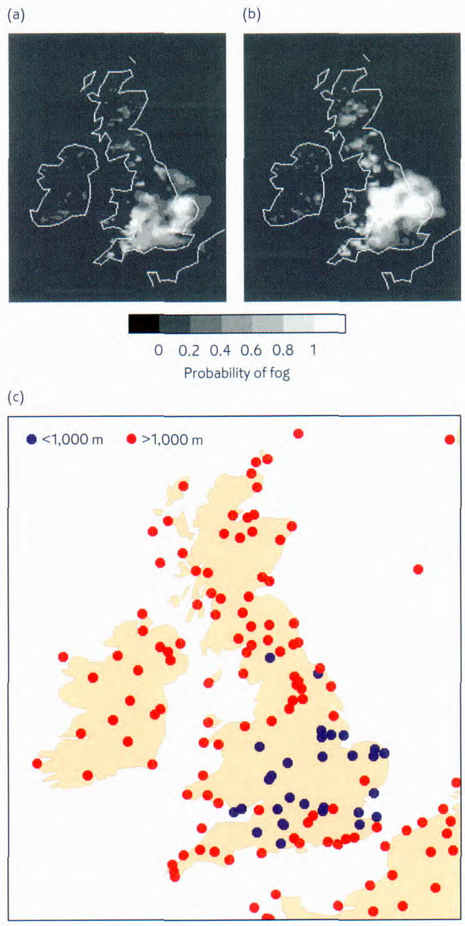


Figure 39. Six-hour forecasts of probability of fog comparing (a) the old data assimilation scheme with (b) 3DVAR and (c) the verifying visibility observations. The forecasts used the UK mesoscale model and verify at 12 UTC on 22 December 1998.

We have been studying this process, using potential vorticity as the link to both the imagery and the dynamical structure. Figure 40 depicts the analysed and forecast tracks from 06 UTC on 23 December 1997; the 'Christmas Eve' storm. Using a conceptual model interpretation of model fields and satellite imagery, the error in the initial field was deduced and corrections made. Rerunning the model from the modified analysis gives the much improved track shown by the blue squares.

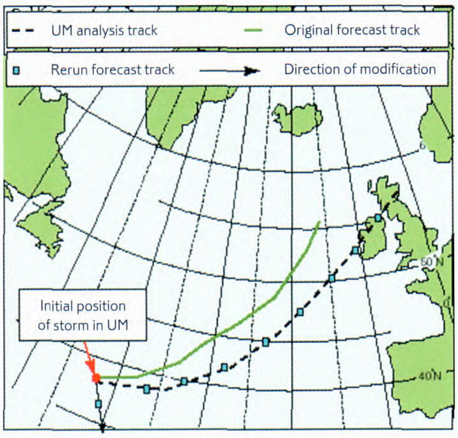


Figure 40. The observed track and the forecast track from 06 UTC on 23 December 1997; the 'Christmas Eve' storm. A rerun of the forecast using a modified analysis based on a subjective interpretation of Meteosat water vapour channel imagery resulted in the track shown by the blue squares.

Development of future forecast models

Use of water vapour imagery to improve forecasts

Using knowledge of the structure of weather systems, forecasters can sometimes use information about the upper troposphere from Meteosat water-vapour channel imagery to improve forecasts.

This study has involved the development of new techniques for calculating basic model variables, such as wind and temperature, from potential vorticity, as well as subjective methods for assessing model error. These techniques will be used in ongoing research into incorporating the synoptic dependence of errors, and improving the dynamical balance, in model analyses.

Mesoscale model validation

Data from the Fronts and Atlantic Storm Track Experiment (FASTEX) have been used to validate the UM at high (mesoscale) resolution. The treatment of cloud and precipitation within the model has been shown to be important in determining the fine structure of rapidly developing secondary cyclones. As an example, Fig. 41 shows the impact of varying the fall speed of ice over a range that broadly encompasses the likely uncertainty in the parametrization. The forecast location and depth of a system are hardly affected by such changes, but there is a significant and systematic impact on frontal structures. The cold front tends to be enhanced by reduced fall speed, with a tendency to induce secondary frontal rain bands, as a result of enhanced ice evaporation below cloud, while warm fronts tend (less systematically) to be weakened by changes in the glaciation within cloud.

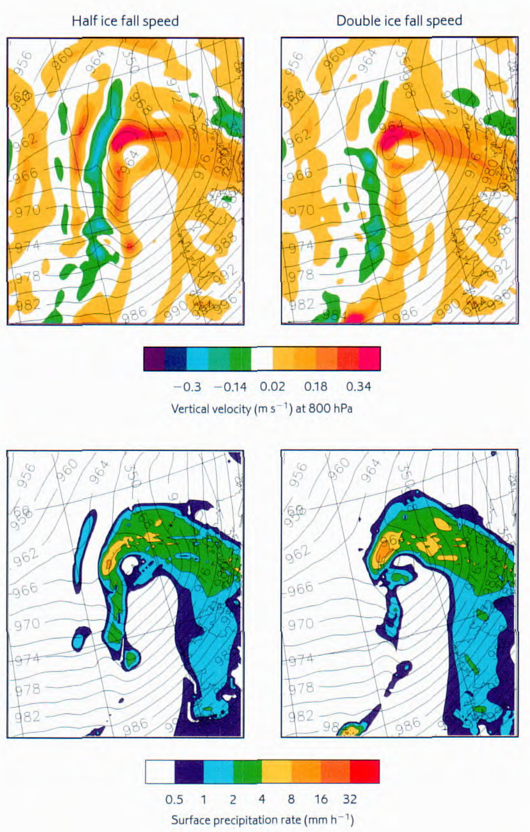


Figure 41. Details from rerun forecasts of a secondary cyclone observed during FASTEX IOP 16 (17 February 1997). The top figures show vertical velocity at 800 hPa, the lower the surface precipitation rate. The left-hand panes show the impact of halving the coefficient determining ice fall speed; the right-hand panes show the impact of doubling it. In this case, increased fall speed verifies better.

Simulating the quasi-biennial oscillation

The quasi-biennial oscillation (QBO) dominates variability in the tropical stratosphere where it appears as alternate bands of descending westward and eastward wind with a period of around 28 months. Despite being one of the most striking examples of low-frequency variability observed in the Earth's atmosphere, the QBO has, until now, been notoriously difficult to capture in numerical simulations with global models.

A realistic simulation of the QBO has been obtained (Fig. 42) using a vertically-extended version of the UM with additional resolution in the stratosphere, and by including the effects of a spectrum of sub-gridscale buoyancy (gravity) waves using a scheme developed at Cambridge University. The scheme applies the additional drag on the atmosphere caused by the dissipation of gravity waves whose phase speeds and wavelengths cannot be explicitly represented in the UM. These forces are necessary to help drive the QBO.

The ability to predict the evolution of the QBO may lead to direct benefits in seasonal forecasting, most notably improving our ability to predict the onset of the monsoon and even the frequency of hurricanes, since the QBO is known to modulate the atmospheric conditions necessary for the occurrence of these events.

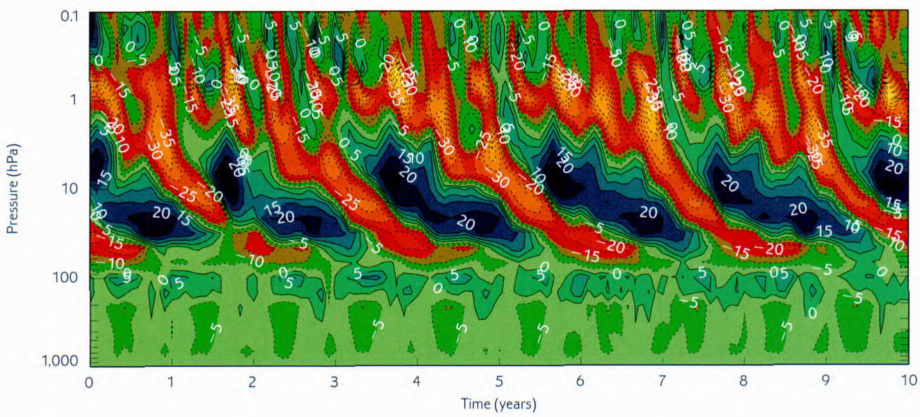


Figure 42. Unified Model simulation of zonal wind over the equator for a period of 10 years showing the quasi-biennial oscillation in the lower stratosphere and the semi-annual oscillation in the upper stratosphere near 1 hPa. The winds have been averaged over all longitudes and are shown between 1,000 hPa near the surface and 0.1 hPa in the mesosphere. The contour interval is 5 m s^{-1} and eastward winds are shown in blue.

Future satellite instruments

Within the next five years, advanced satellite instruments will add to the observations available for use in NWP; research is under way to provide the scientific basis required to understand the data available from these instruments and to prepare for their operational exploitation. Several new instruments are planned; we report here on preparations for two of them.

The METOP satellite series will carry the Infrared Atmospheric Sounding Interferometer (IASI), to provide high-resolution infrared spectra

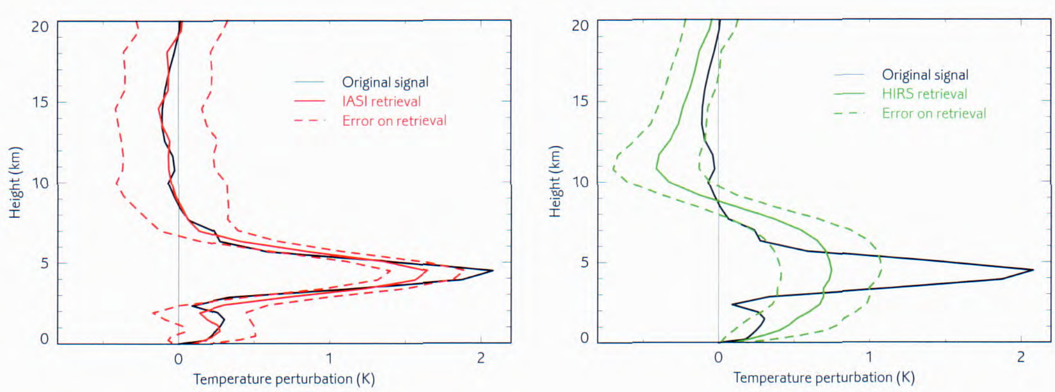


Figure 43. A 'forecast error profile', i.e. a perturbation in the atmospheric structure not captured by the NWP model, can be sensed by a satellite instrument and retrieved with an accuracy dependent on the characteristics (noise, spectral resolution, etc.) of the instrument. The temperature perturbation (black) can be retrieved much better for IASI than for the current HIRS instrument.

containing temperature and humidity information with vertical resolution much enhanced compared with current instruments. Preparations to process and assimilate these data are under way, and these include studies of our ability to sense and retrieve typical perturbations in the atmosphere's vertical structure which are known to lead to substantial forecasting errors (Fig. 43).

The Global Positioning System (GPS) can yield information on atmospheric structure via the radio occultation technique (Fig. 44). Data from receivers on low Earth-orbiting satellites can provide profiles of atmospheric refractivity (and hence information on profiles of temperature and humidity). METOP will carry such receivers, and data from earlier experimental satellites will allow us to understand the characteristics of these data and prepare to assimilate them effectively.

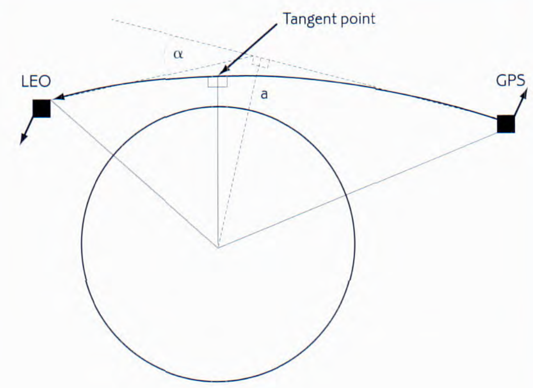


Figure 44. Radio occultation: when a radio wave propagates through the Earth's atmosphere, its path is bent by refractive index gradients. The change in bending angle with position of a low Earth-orbiting satellite can be inverted to recover a refractive index profile and, subsequently, temperature, humidity and surface pressure information.

Atmospheric Processes Research

Atmospheric Processes Research uses sophisticated observational facilities and detailed high-resolution models to determine how processes should be represented in numerical weather prediction and climate models.

INTERACTION OF THE SURFACE WITH THE ATMOSPHERE

The numerical forecast model uses parametrizations to specify the rate at which heat and moisture are transferred into the atmospheric boundary layer from the surface. Although these processes are relatively well understood and specified for level terrain, it is only recently that high-resolution models have been used to investigate the effect of mountains. In particular, such models predict that separation of the airflow in eddies from the lee slopes of valleys should have a pronounced effect on the average heat and moisture fluxes.

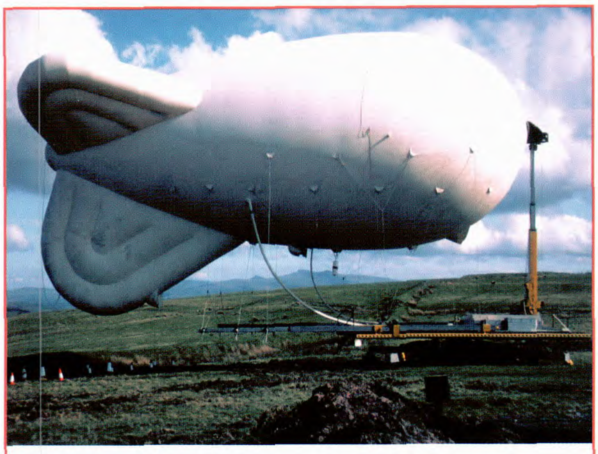


Figure 45. The Met. Research Unit's helium-filled kite balloon swinging to its mast mooring on a ridge site near the Brecon Beacons. It is capable of lifting up to ten turbulence probes to heights of over 1.5 km above the surface.

To directly measure these fluxes in such terrain, we detached to a mountainous site in Wales in May 1999. Simultaneous measurements were made at a number of surface sites on ridges and in valleys, and also from probes mounted to the tethering cable of a kite balloon. All data were telemetered by radio links to a ground station for later processing and intercomparison with model predictions (Figs 45 and 46).

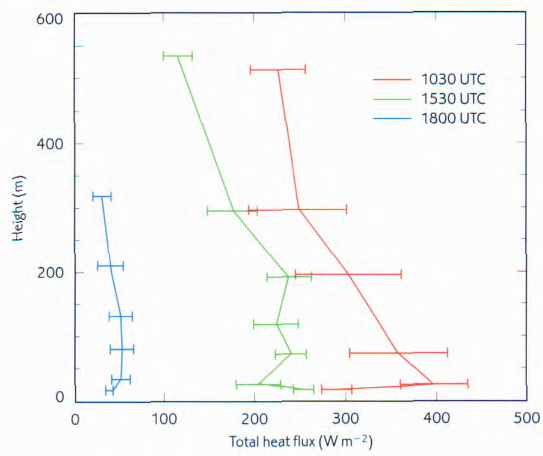


Figure 46. Plot of vertical profiles of total heat fluxes (i.e. sensible plus latent heat) at three periods on 25 May 1999. By the evening the large daytime fluxes have become considerably reduced.

Larger-scale flows – mountain waves

The Mesoscale Alpine Programme (MAP) is an international project with participation from ten European countries, Canada and the USA. It is an integrated experimental and numerical modelling campaign designed to observe and improve the understanding of mountain-influenced precipitation events and the dynamics of certain mountain-flow phenomena such as upper-level gravity-wave breaking. The project officially began in Autumn 1994, culminating in a ten-week

Special Observing Period (SOP) in Autumn 1999, during which a significant number of extra observational platforms were collocated within the alpine region. The MRF C-130 aircraft made measurements of gravity waves from the end of October to mid-November 1999. For these flights we were joined by the American Electra from the National Center for Atmospheric Research and the German Falcon from the Deutsches Zentrum für Luft- und Raumfahrt. Four joint missions with all three aircraft were flown. The combined flight-level data, including dropsonde data from each aircraft, and remote-sensing lidar data from the Electra and Falcon, make these missions some of the most carefully measured atmospheric gravity wave systems to date.

The main motivation for the MAP gravity-wave dynamics sub-project is to test the ability of modern numerical weather prediction models to accurately predict and represent mountain-forced gravity waves generated by complex terrain. Point source or line-averaged airborne flight-level data and remotely sensed observational data can be compared with model predictions to validate and develop the models.

On 2 November 1999 the three research aircraft flew a mission over the western Alps, flying repeat legs at three different altitudes. Figure 47 shows the observed waves over and downstream of Mont Blanc (4,808 m) which, combined with the full time-sequence of data, gave indisputable evidence that the wave system was in a steady state. In spite of the great height of Mont Blanc the observed waves were rather small. Vertical profiles through the atmosphere from upstream observations show that the small-wave amplitude is due to a stagnant layer of air, up to 3,250 m above mean sea level, caused by the nearby lower mountains to the south-west. This reduces the effective mountain height of Mont Blanc and its neighbours. High-resolution modelling studies will help explain further the dynamical mechanisms important in this case. In addition, comparisons of model diagnostic quantities with aircraft observations will help in understanding similar situations (Fig. 48). The comprehensive nature of the MAP observational data set offers significant potential for verifying and improving orographic drag parametrization schemes, and as a test-bed for high-resolution forecast models.

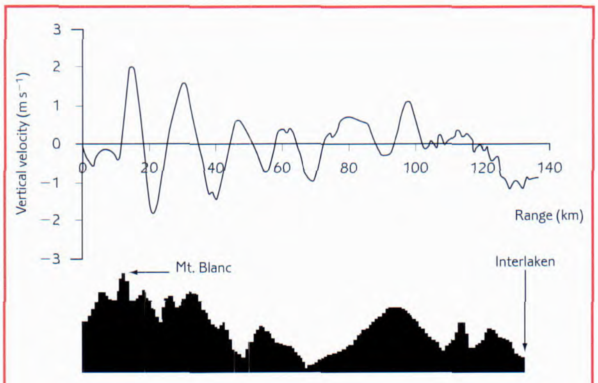


Figure 47. Vertical velocity measurements from the C-130 aircraft of mountain-generated gravity-wave activity in the western European Alps on 2 November 1999 during the MAP SOP. The aircraft was flying at an altitude of 7.62 km AMSL with the atmospheric flow from left to right. The observations correspond to the second of eight repeat legs flown by the aircraft along the same flight path. A schematic representation of the underlying topography during the flight is also included.

Detailed cloud microphysics

Just prior to MAP, the MRF C-130 took part in another mountain wave experiment over Scandinavia with collaborators from university groups in Sweden, Germany and Britain. The project, called INTACC (Interaction of Aerosol and Cold Clouds), is partly funded by the European Union with the objective of quantitatively understanding the mechanisms by which ice crystals are formed in the atmosphere. Lee wave clouds that form over and downwind of mountain ranges

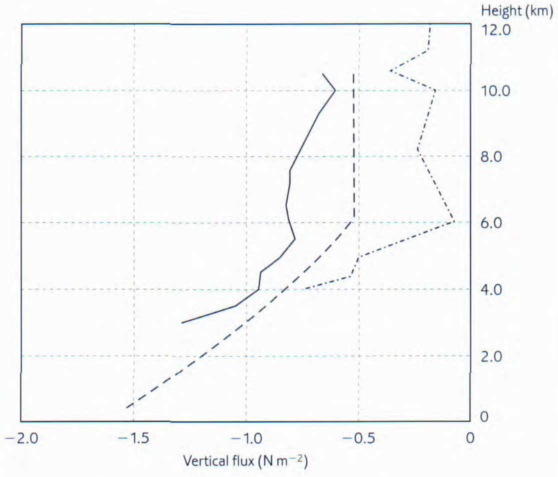


Figure 48. ***Profiles of the vertical flux of horizontal momentum from a gravity wave field observed on 15 October 1990 over the Pyrenees during the Pyrenees Experiment (PYREX). The solid line represents the area-averaged flux from a high-resolution non-hydrostatic numerical model integration, the dashed line the Unified Model's sub-gridscale gravity-wave-drag parametrization scheme, and the dot-dashed line the calculated line-averaged flux from aircraft observations. Note the trend in the profiles of flux with height all compare favourably with one another, indicating good agreement in diagnosed mean flow decelerations due to the gravity-wave activity.***

provide a simple case to observe and understand the processes involved in ice formation.

A number of new instruments were used on this detachment which make the resulting data set unique. Firstly, a small-ice detector (SID) developed by the University of Hertfordshire for use on the aircraft that is capable of determining whether particles as small as two microns in size are liquid or ice. Secondly a probe, developed by the University of Manchester Institute of Science and Technology (UMIST), that can detect aerosol that ice can form directly onto, was also flown. In addition to these newer probes we also flew instruments capable of measuring aerosol characteristics and trace gases, supplied by the University of Stockholm, University of Sunderland, University of East Anglia, UMIST, and the Max Planck Institute.

The aircraft was based at a Swedish Air Force base near Östersund in central Sweden, within 1.5 hours flying time of the northern and southern tips of Scandinavia. During the flights we would locate isolated lee-wave clouds (Fig. 49) and sample the cloud droplets, ice crystals and aerosol outside cloud by flying through them parallel to the wind direction at a variety of altitudes. By comparing the observations with results from a detailed microphysical cloud model (Fig. 50) we are currently investigating the processes that convert the liquid drops into ice crystals.

Using a cloud-resolving model

A numerical model which resolves the important dynamical scales of a cloud or cloud system is commonly referred to as a cloud-resolving model (CRM). CRMs are an increasingly used tool to diagnose quantitative information about clouds which is impossible to obtain using conventional observations. If the CRM data are to be relied upon in the development of new parametrizations of cloud processes for use in large-scale models, then it is necessary that they should be tested and validated against observational data.

One area of interest involving the use of CRMs is the study of feedbacks between convection and the radiative heating generated by convective cloud. Here, it is important that the CRM should generate realistic cloud microphysical properties over the whole convective life cycle. Simulations of tropical convection have been performed using a CRM forced by observed large-scale tendencies of temperature and moisture taken from a period during the TOGA-COARE experiment in the western Pacific. The simulated cloud fields have then been sampled in a way which attempts to reproduce aircraft measurements of cloud microphysical properties in the anvil regions of tropical convective clouds.

Figure 49. A classic isolated lee-wave cloud photographed from the C-130 during INTACC.

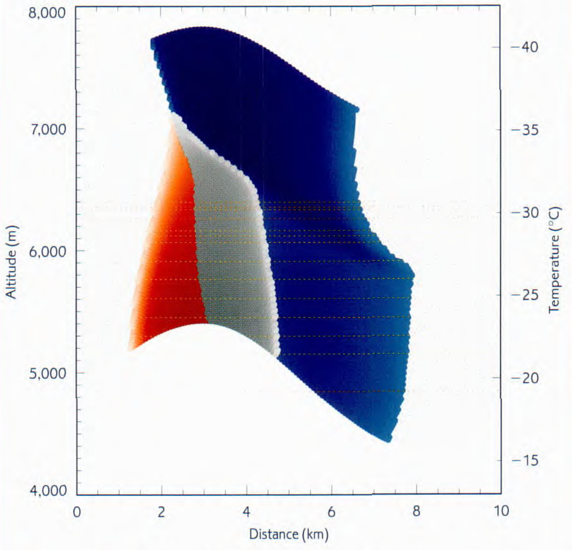


Figure 50. A synthetic cloud modelled to match the measurements of the cloud shown in Fig. 49. The simulation is the result of many combined runs of a parcel model that is capable of simulating the formation of liquid water drops and their subsequent possible conversion to ice. In both this figure and Fig. 49 the air flows in from the left and ascends to produce droplets that define a sharp edge. The liquid water droplets then freeze and flow out of the cloud to the right as ice crystals that give rise to a hazy appearance. Blue is ice, orange is liquid water and grey is a mixed phase region where both liquid and ice are present. Darker colours indicate increased condensed water content.

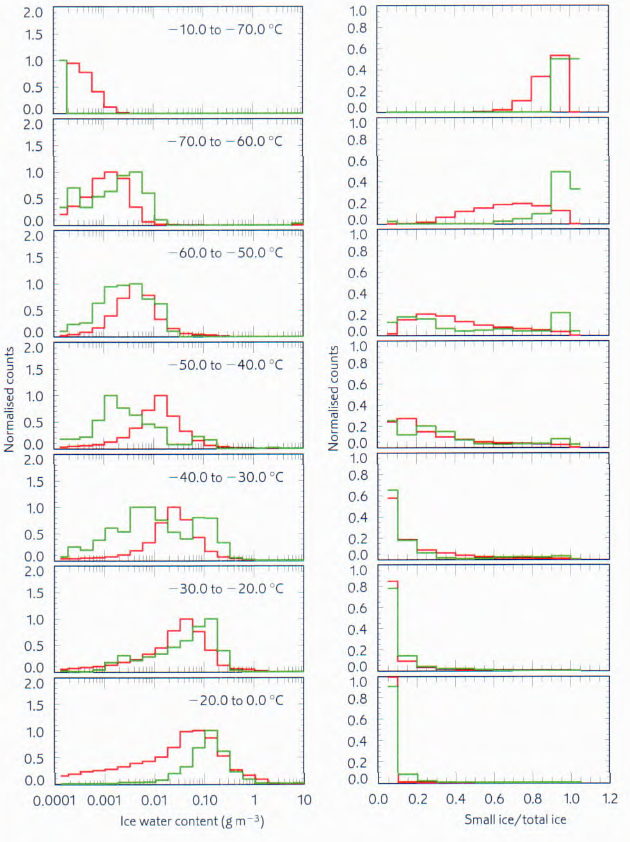


Figure 51. A comparison of measurements with CRM simulations. The green histograms are obtained from aircraft measurements in the anvils of a number of tropical maritime convective systems in the vicinity of Kwajalein (Marshall Islands) and are by courtesy of AJ Heymsfield (NCAR). The red histograms are obtained by sampling the anvil regions of CRM-simulated cloud fields (i.e. excluding active convective updraughts) at a number of times during a simulation. The left column shows the relative frequency of IWC values in each of seven temperature ranges, and the right column, for the same temperature ranges, the relative contribution of small (sub-200 micron) particles to the total IWC. A value of zero implies that the whole IWC is in particles larger than 200 microns while a value of one indicates that it is all in particles below this limit.

Figure 51 shows the relative frequency of ice water content (IWC) values in a number of temperature ranges as sampled from aircraft and CRM. The model does a good job in predicting the mode IWC in each temperature range and its decrease with temperature. The CRM predicts both the mass and number concentration of three ice species (pristine crystals, aggregates and graupel/hail), each of which has a parametrized representation of its particle size distribution. The latter may be evaluated at each model grid point to determine the fraction of the total IWC which is contained in particles below a chosen size threshold (200 microns). The relative frequency of values of the small particle IWC to total IWC ratio is also shown. The model successfully predicts the dominance of large particles for temperatures warmer than –40 °C and the increasing contribution of smaller particles at colder temperatures. However, it tends to maintain some contribution to total IWC from large particles even at the coldest temperatures which is not observed.

This comparison shows that the CRM produces a realistic variation of IWC with temperature, a necessary condition for the study of cloud-radiation interactions. It may, however, produce too much aggregation of the small ice particles at cold temperatures, so that particle-effective radii used for radiative heating calculations should not yet be calculated interactively from the CRM's parametrized size distributions.

Simulating shallow convection

For several years we have been leading participants in an international collaborative series of workshops designed to examine and improve the skill of both Large Eddy Simulations (LES) and single-column models in representing a variety of observed cloud types. A LES is a numerical simulation that resolves the turbulent eddies that are responsible for the bulk of the transport. They are increasingly used across the world to develop the parametrizations employed by the single-column models. For shallow convection, a resolution of around 50 m is required. The most recent meeting on boundary-layer clouds focused on the diurnal cycle of shallow cumulus convection over land. We specified and co-ordinated the case which was based on data from the Southern Great Plains ARM site in the USA. The results from eight different large-eddy models were found to be generally in excellent agreement, both with each other and the available observations within the expected uncertainties. In addition, further tests performed showed that the results were encouragingly insensitive to factors such as resolution and the detail of the sub-grid model. This agreement can be seen in Fig. 52, which shows the evolution of cloud top and base from all the different LES.

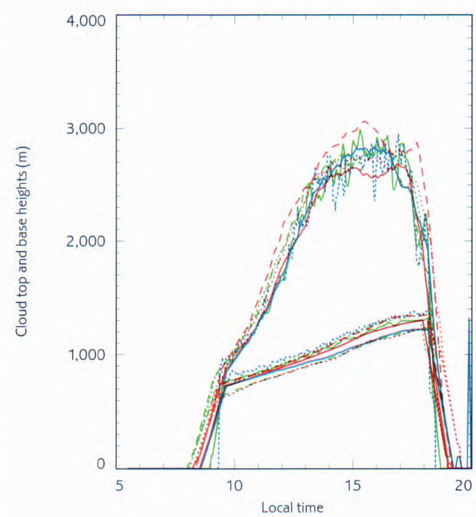


Figure 52. Time-series of the height of cloud top and base from eight different LES (identified by colour or line style).

Outside this international work, some earlier marine shallow cumulus case-studies were used as a basis for an extensive LES study of the ensemble properties of shallow cumulus clouds. These results were then used, in collaboration with the Model Parametrization Group, to identify and develop scalings for the parameters that control the transports of heat, moisture and momentum in shallow cumulus-capped layers. A key parameter in the scheme used to represent shallow cumulus transports in the UM is the rate of lateral entrainment into the cloud ensemble. Profiles of this quantity from a range of LES, including the recent diurnal study, are shown in Fig. 53, while Fig. 54 shows that application of the scaling collapses the data reasonably well onto a single line.

Continuing close collaboration with the Model Parametrization group has ensured that these results have already been successfully implemented in the single-column model version of the UM and global testing is now under way.

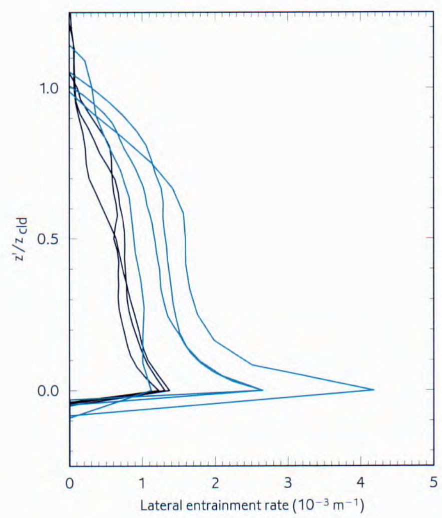


Figure 53. Lateral entrainment rate from LES with different initial conditions including both the weakly forced marine cases (coloured lines) and more strongly forced land cases (black lines). z' is the height above cloud base and z_{cld} the cloud depth.

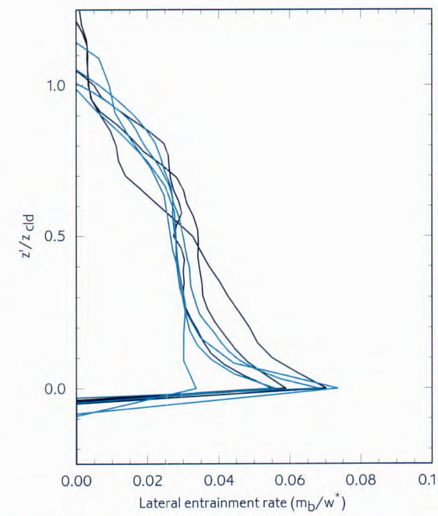
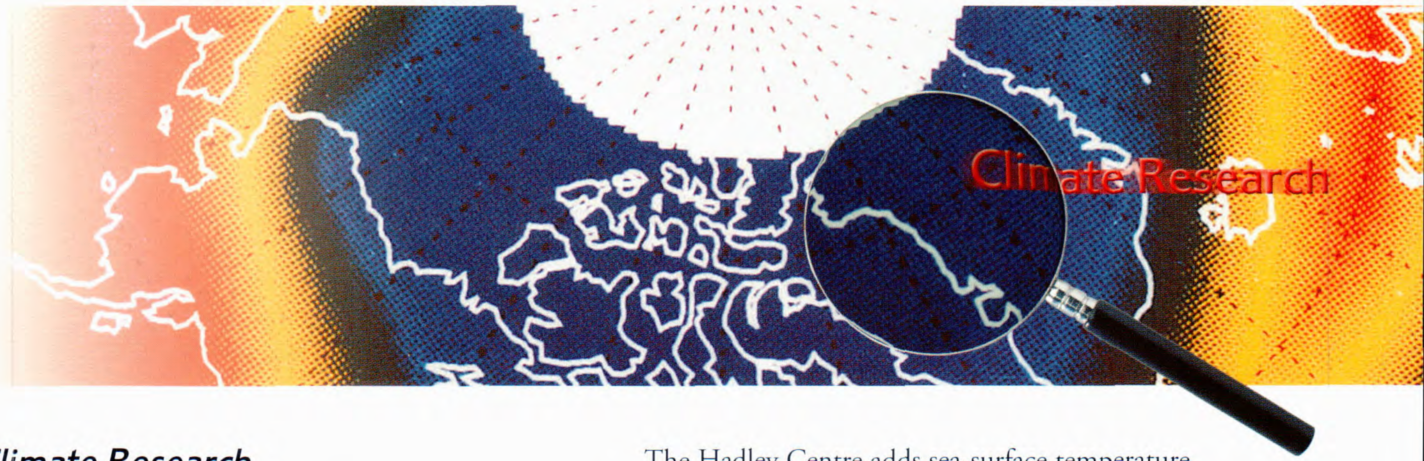


Figure 54. Similar to Fig. 53 except the lateral entrainment rate is now scaled by the cloud depth, cloud-base mass flux (m_b) and a cloud velocity scale (w^*). In comparison with Fig. 53, the scaling is seen to provide a means to predict the lateral entrainment for a range of different conditions.



Climate Research

Climate Research has two main customers. First, the Department of the Environment, Transport and Regions seeks the best possible estimates of future climate changes due to human activities, in order to inform UK policy towards the United Nations Framework Convention on Climate Change (UNFCCC). Second, the Ministry of Defence, as part of its Public Meteorological Service research programme, funds the development and validation of the climate model, climate monitoring, and work on atmospheric dispersion and atmospheric chemistry.

CLIMATE VARIABILITY

Monitoring global climate

Monitoring global climate is important both to understand variability and to investigate climate change. One of the most significant achievements of the Hadley Centre for Climate Prediction and Research is the ongoing record of global surface temperature. This is prepared with the University of East Anglia (UEA), and used by the Intergovernmental Panel on Climate Change (IPCC) in its assessments of the science of climate change.

Recent climate and extremes

In 1999, the global average temperature near the surface of the earth was the fifth highest on record. It was estimated to be 0.33 °C higher than the 1961–90 average. However, the global average temperature in 1999 was cooler compared with 1998, due to the persistent cool La Niña event in the tropical Pacific Ocean. Even so, no recorded year with a major La Niña event was as warm globally as 1999.

The Hadley Centre adds sea-surface temperature (SST) observations to the global picture, and we have recently tested the accuracy of bias corrections to the SST data set, as these can have a considerable effect on our estimates over the past century.

Surface temperatures

We created an improved monthly historical SST analysis, with smaller local random errors than previous analyses, to make it more suitable for extreme value analysis. This new analysis contributed to a new Hadley Centre sea-ice and sea-surface temperature data set (HadISST1), which was made available to ECMWF for their 40-year re-analysis and to the CLIVAR Climate of the Twentieth Century project.

HadISST1 contains monthly data from 1871 to 1999 and uses an improved analysis method based on a form of optimum interpolation suitable for data that have large gaps. It also has more homogeneous sea-ice concentrations than previous analyses, and is more temporally and spatially coherent, especially in the era of satellite data (from 1982 onwards).

Radiosonde temperatures and Microwave Sounding Unit (MSU) retrievals

An analysis of tropical radiosonde temperatures since 1958 has shown geographically coherent interdecadal variations in the temperature difference between the surface and the lower- to mid-troposphere. These variations exceed inter-regional variations in instrumentation. They suggest that real variations in the lower-tropospheric lapse rate of temperature may explain much of the difference between surface and tropospheric tropical temperature trends over the past 20 years.

We contributed to a US National Research Council report on reconciling surface and tropospheric temperature trends over the past 20 years.

Highlights of this report include the following observations.

- Since 1979 the surface has warmed by 0.25–0.4 °C and the lower- to mid-troposphere by 0.0–0.2 °C
- The difference between satellite and surface temperature trends in no way disproves the conclusion that global surface temperature has risen substantially since the beginning of the 20th century
- The observed trends have been partly reconciled with climate model simulations of human-induced climate change
- The evidence suggests that much of the difference between the surface and tropospheric temperature trends results from real physical effects, including volcanic eruptions and anthropogenic forcing, but with important contributions from measurement and sampling errors.

A worldwide analysis of extreme warm night-minimum temperatures shows an increasing frequency over the past 50 years (Fig. 55). This analysis forms part of a set of results on the occurrence of extremes collated through a joint Commission for Climatology/CLIVAR Task Group in support of IPCC and other assessments.

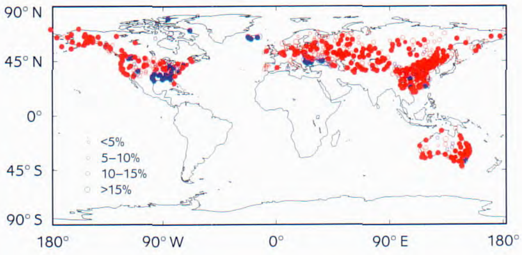


Figure 55. Change (%) of the annual fraction of warm night-time temperatures (minimum temperature >90th percentile of daily observations over the 1961–90 period). Red is a positive change, blue a negative change. Filled dots indicate stations that show a significant change between two non-overlapping post-World War II multidecadal averages.

UK climate in 1999

In central England, 1999 was equal warmest year with 1990 and 1949 in the 341-year record history. For minimum (night-time) temperatures, 1999 was the warmest year in the 122-year record history, whereas several previous years were warmer for maximum (daytime) temperatures.

Throughout 1996–99, the England and Wales Precipitation (EWP) series has been updated in a manner consistent with the existing UEA Climatic Research Unit series for 1766–1995, to give a corresponding monthly series. We now possess a particularly consistent daily and monthly series of EWP since 1931. The provisional annual total for EWP in 1999 was the eleventh largest since 1931, while 1998 was the fifth wettest year in this period.

In collaboration with the Ocean Applications Branch, we have used multiple linear regression to make hindcasts of global surface temperature for 1949–98, an independent hindcast for 1999, and a forecast for 2000, along with error estimates (Fig. 56). The predictors included indices of the El Niño Southern Oscillation (ENSO), an inter-hemispheric contrast pattern in SST, volcanic aerosol, solar irradiance, and estimates of anthropogenic global mean net radiative forcing at the tropopause, all measured just before the target year. The anthropogenic forcing included the effects of greenhouse gases, the direct and indirect influence of sulphate aerosols, and also ozone changes in the stratosphere and troposphere.

The hindcasts with six predictors scored a correlation of 0.90 with that observed, even though they were based on a set of regression equations that excluded the period from five years before to five years after each target year. Most of the skill was retained if a coupled model prediction of ENSO for the first half of the target year was used instead of the observed state of ENSO just before the target year. The hindcast for 1999 of 0.36 °C was close to that observed (0.33 °C). The prediction for 2000, from the average of an equation using the coupled model prediction of ENSO and two regression equations that used observations of ENSO in late 1999, is 0.38 °C with error bounds, measured by the 20% and 80% cumulative probabilities of 0.30 °C and 0.46 °C.

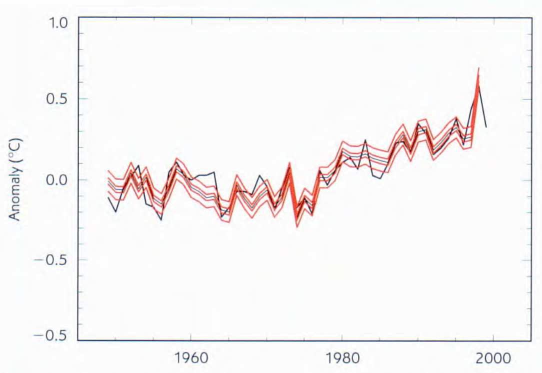


Figure 56. Hindcasts and forecasts (thin black line) of global mean temperature departure from 1961–90 climatology. The 20th, 40th, 60th and 80th percentiles of the hindcasts and forecasts are shown as brown lines and the observations as a heavy black line.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was set up in 1988 to provide periodic assessments of current scientific consensus about climate change, its potential impacts and the range of possible response strategies. The focus of the IPCC's Working Group I (WG I), co-ordinated by a technical support unit based at the Hadley Centre, is the physical climate system. IPCC WG I produced two major assessments, in 1990 and 1995, plus several special reports and technical papers. These reports, written by international teams of the world's leading scientists, have played a major role in the negotiation and implementation of the UN Framework Convention on Climate Change (FCCC).

This year, IPCC WG I completed and published its special report, *Aviation and the global atmosphere.* It is the most comprehensive assessment available of the effects of aviation on the global atmosphere. It considers all the gases and particles emitted by aircraft into the atmosphere and the role they play in modifying the chemical properties of the atmosphere and initiating the formation of contrails. The report then considers how all this can change the radiative properties of the atmosphere, leading to climate change, and how the ozone layer can be modified, leading to changes in ultraviolet radiation reaching the Earth. The report also discusses how potential changes in aircraft technology, air transport operations, and the institutional, regulatory, and economic framework might affect emissions in the future.

Preparations are well under way for the third major IPCC assessment report, due to be completed in early 2001. In addition, in partnership with Working Group II, the Task Group on Climate scenarios for Impact Assessment (TGCIA) continues to provide a common set of climate scenarios to the climate impacts community through a data distribution centre.

Figure 57 shows estimates of the globally and annually averaged radiative forcing (a measure of the importance of a potential climate-change mechanism) from subsonic aircraft emissions in 1992 (Fig. 57(a)) and in 2050 for scenario Fa1 (Fig. 57(b)). Scenario Fa1 is a reference scenario which assumes technology for both improved fuel efficiency and NO_x reduction. The available information on cirrus clouds is insufficient to determine either a best estimate or an uncertainty range; the dashed line indicates a range of possible best estimates. The estimate for total forcing does not include the effect of changes in cirrus cloudiness. The uncertainty estimate for the total radiative forcing (without additional cirrus) is calculated as the square root of the sums of the squares of the upper and lower ranges for the individual components. The evaluations below the graph ('good', 'fair', 'poor', 'very poor') are relative appraisals associated with each component, and indicate the level of scientific understanding. They are based on the amount of evidence available to support the best estimate and its uncertainty, the degree of consensus in the scientific literature and the scope of the analysis. This evaluation is separate from the evaluation of the uncertainty range represented by the lines associated with each bar.

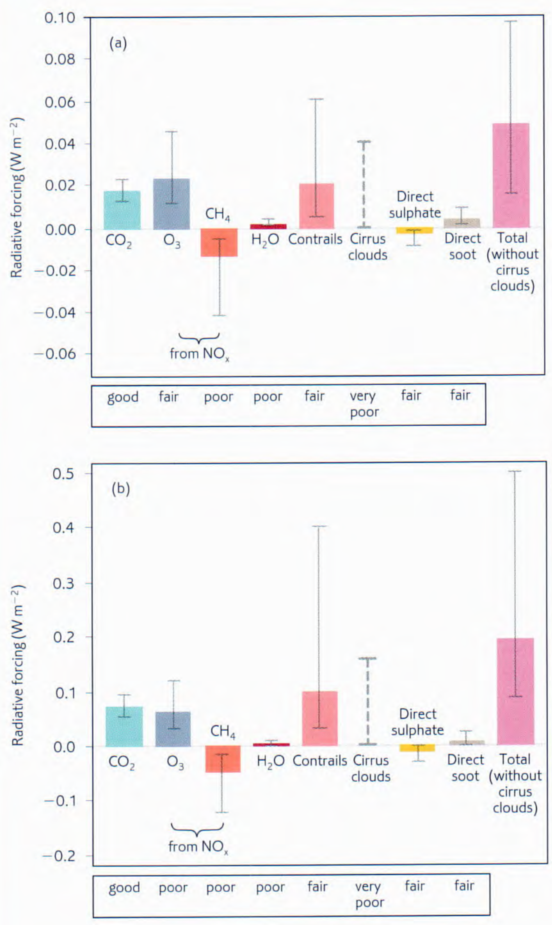


Figure 57. Estimates of the globally and annually averaged radiative forcing (W m^{-2}) from subsonic aircraft emissions in 1992 (a) and in 2050 for scenario Fa1 (b). The scale in (b) is greater than that in (a) by about a factor of four. The bars indicate the best estimate of forcing, while the line associated with each bar is a two-thirds uncertainty range developed using the best knowledge and tools available at the present time. The two-thirds uncertainty range means that there is a 67% probability that the true value falls within this range.

Model development and parametrizations

We are continuously improving our climate model by incorporating more-realistic parametrizations of processes in the atmosphere that take place at scales not resolved by the model grid.

Representation of precipitation and cloud

Clouds are one of the most important elements of the atmosphere that need to be represented accurately in climate models. Most of the spatial and temporal variability of the heating of the atmosphere and surface arises from the ever-changing distribution of clouds and precipitation — factors that are believed to be crucial in determining the response of the system to climate variability and change. Therefore, we are continuing to work towards more-accurate representations of clouds and precipitation in the model. In particular, we have extended the new mixed-phase precipitation scheme introduced into the mesoscale forecast model in August 1998 (see the *Scientific and Technical Review 1997/98*), and have determined its impact on the climate model.

One consequence of including the new scheme in the model is that ice-water contents in the upper troposphere are increased. Figure 58 illustrates this for the deep convective region over tropical Africa. (Note the much denser shading at upper levels within the convective system.) This increase changes the distribution of latent heating in the model and affects the radiative properties of the clouds. This alters the balance between the radiative heating of the atmosphere and surface. In parallel with this work, more-accurate formulations of the radiative properties of ice crystals are being included in the model, which, together with the mixed-phase scheme, should lead to more-reliable simulations of the important role of ice clouds in the climate system.

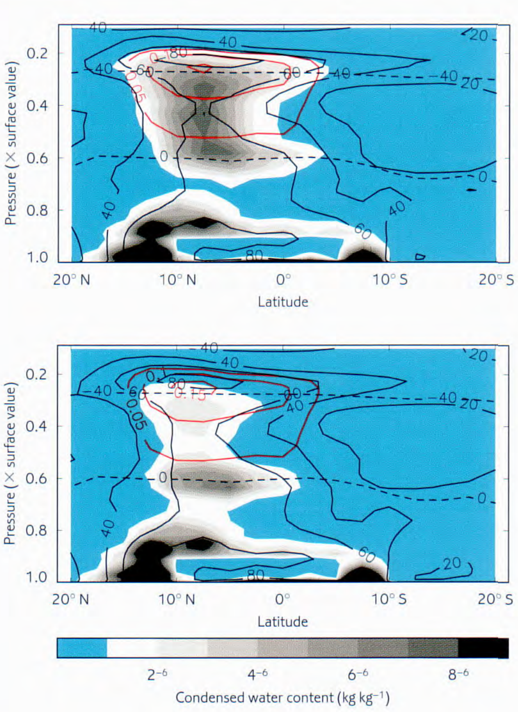


Figure 58. North–south cross-section through the Inter-tropical Convergence Zone over Africa, for a June to August 10-year mean. The condensed water contents (kg kg^{-1}) are shaded lines, temperatures (°C) are dashed, relative humidities (%) are shown as solid lines and the convective cloud fraction is shown in red. The upper plot is from the new mixed-phase scheme and the lower plot is from the temperature partition scheme. The vertical co-ordinate is pressure, normalised by the surface value.

Aerosols and climate

Several types of atmospheric aerosol may now be treated in the climate model, including sulphate aerosols from natural and anthropogenic sulphur sources, sea-salt, aerosols from biomass burning and also mineral dust.

The most well known source of mineral dust is the Sahara Desert, from which extensive plumes may often be seen in Meteosat images, extending over the eastern tropical Atlantic. Progress with modelling the distribution and radiative impact of this dust has continued. Six size-classes of particle are used and the production of dust depends on the surface wind, soil moisture content, soil type and vegetation cover. The Saharan plume is rather well simulated, but dust production from China is weaker than implied by observations. Figure 59 displays the annual mean net radiative forcing due to dust in a present-day climate simulation. The mixture of positive and negative values is due partly to competition between the different effects on solar and terrestrial radiation, to contrasting surface albedos, and to radiative interaction with cloud.

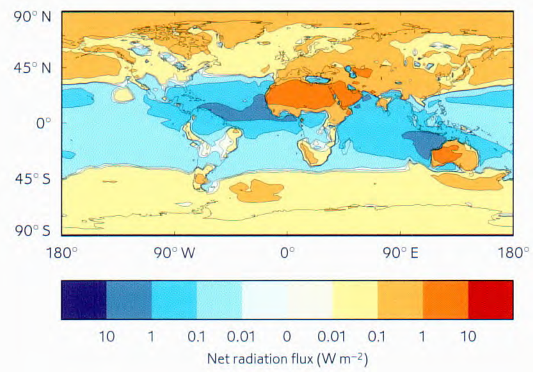


Figure 59. The annual mean change (W m^{-2}) in net radiation flux at the top of the atmosphere due to mineral dust, averaged over a five-year experiment with the climate model.

A large number of experiments with the sulphur cycle model, using different scenarios of future sulphur and black carbon emissions, have provided input to the IPCC WG I report.

Carbon cycle

Currently less than half of the human emissions of carbon dioxide (CO_2) remain in the atmosphere. The remainder is absorbed by the oceans and by vegetation and soils on land. These natural components of the carbon cycle are 'buffering' the earth system by removing a significant fraction of the emissions from the atmosphere, where they would otherwise lead to greenhouse warming. However, this situation may change in the future. Land–atmosphere and ocean–atmosphere fluxes of CO_2 are known to be sensitive to climate, so there is a potential for the 'airborne fraction' to alter, initiating a climate–carbon cycle feedback loop.

To date, general circulation model (GCM) predictions of climate change have neglected this feedback mechanism, as they have been driven with future CO_2 concentrations derived from emission scenarios using off-line models. To assess the importance of this, we have developed a coupled climate–carbon cycle model at the Hadley Centre, in which atmospheric CO_2 is updated interactively, based on the emissions, and is consistent with the impact of the modelled climate on the land and ocean uptake. The model is built around a version of the HadCM3 ocean–atmosphere GCM, which is coupled to sub-models of the ocean–carbon cycle (HadOCC, developed in collaboration with Southampton Oceanography Centre) and of the land–carbon cycle (TRIFFID, developed in collaboration with the Institute of Hydrology).

The first transient climate–carbon cycle simulation has recently been performed with this model, driven with CO_2 emissions consistent with the IS92a ('business as usual') scenario. Figure 60 summarises some results from this run. The continuous black line shows how the carbon content of the atmosphere changed from 1850–2100. The red, blue and green lines represent the contributions of emissions, ocean flux and land flux respectively, to the atmospheric carbon budget (with negative values representing uptake). The model indicates that the land and ocean have both absorbed significant amounts of carbon between 1850 and the present day. However, land carbon storage is predicted to decrease from the middle of the 21st century as soils and vegetation switch to become sources of CO_2. As a result, the predicted rate of rise of atmospheric CO_2 is much more rapid than usually assumed (shown by the dashed black line) and the associated climate change is also more extreme.

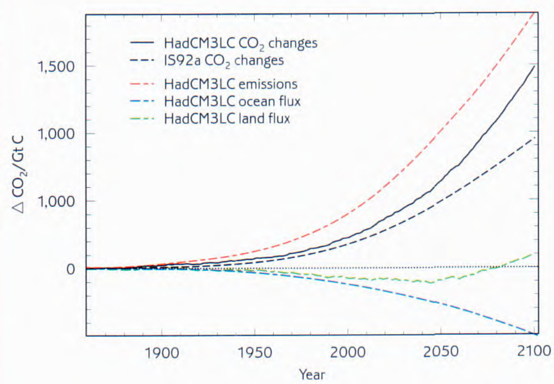


Figure 60. Budgets of CO_2 from the first transient GCM simulation with a fully interactive carbon cycle. The continuous black line represents the change in atmospheric CO_2 from 1850. The red, blue and green lines represent the contributions from emissions and changes in ocean and land carbon storage. The dashed black line shows the change in atmospheric CO_2 as usually assumed in GCM runs.

This is the first estimate of the climate–carbon cycle feedbacks and, although improvements to the model are already under way, it shows that such feedbacks are likely to be very important factors for climate change over the next 100 years.

Atmospheric chemistry modelling

As a result of human activities, atmospheric concentrations of a number of greenhouse gases are anticipated to build up further during the next century. To estimate the rise in global concentrations of methane, ozone and sulphate aerosols from their baseline levels in pre-industrial times through to the present day and beyond, we use a highly sophisticated global three-dimensional (altitude–latitude–longitude) Lagrangian chemistry-transport model (STOCHEM) (Fig. 61).

We are making continual improvements to STOCHEM to increase confidence in the predictions for the rest of the century. STOCHEM now uses emissions from the EDGAR and GEIA databases and emission projections from the IPCC SRES scenarios for methane, carbon monoxide, NO_x, SO_2, ammonia, dimethyl sulphide and non-methane hydrocarbons. We have also made major improvements to the convective transport of trace gases. STOCHEM has been integrated within the UM system and runs fully with the Hadley Centre climate model.

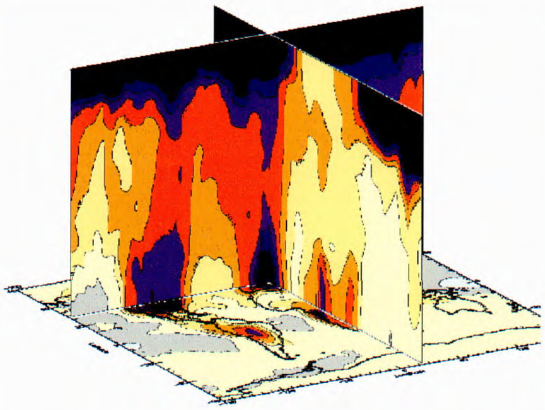


Figure 61. The complex three-dimensional nature of the global fields of tropospheric ozone calculated with STOCHEM for July 1997. This surface-fence cross-plot illustrates the formation of ozone plumes from biomass burning over Africa, photochemical smog formation over North America and southern Europe, and stratosphere–troposphere exchange at the top of the model domain.

Predictions of climate change

We have predicted climate change from 1990 to 2100 using the HadCM3 climate model, with two new scenarios for future anthropogenic emissions (the results have been submitted to the IPCC Third Assessment Report). These scenarios (SRES A2 and SRES B2) are derived from different, but equally likely, assumptions of future socio-economic, technological and energy-use developments.

In addition to the effects of greenhouse gases and sulphur emissions that were included in the results from HadCM3 experiments presented last year, we now explicitly represent projected changes in atmospheric ozone, which are characterised by increases in the troposphere lower atmosphere and reductions in the stratosphere.

HadCM3 was first forced with historical changes from 1860 to 1990, closely reproducing the warming of 0.2 °C per decade observed since about 1970 (Fig. 62, top panel). The A2 and B2 scenarios were then imposed in separate simulations from 1990. Both of these show a steady warming of around 0.2 °C per decade until 2050, leading to significant changes compared to a control simulation with no changes in greenhouse gases or sulphur (Fig. 62, top panel). Beyond 2050, however, the A2 experiment simulates a larger rate of warming than B2. This is due to higher greenhouse gas emissions in A2, coupled with larger reductions in sulphur emissions beyond 2050.

There are also differences between the simulated regional changes. For example, Fig. 62 (bottom panel) shows areas where the A2 and B2 simulations produce statistically significant differences in soil moisture for a 30-year period centred around the 2080s. Parts of the Tropics are wetter in A2, while Iberia (already drier in B2 than in the control simulation) tends to become even drier in A2.

We have also investigated scenarios in which steps are taken to prevent future CO_2 concentrations rising above a certain threshold.

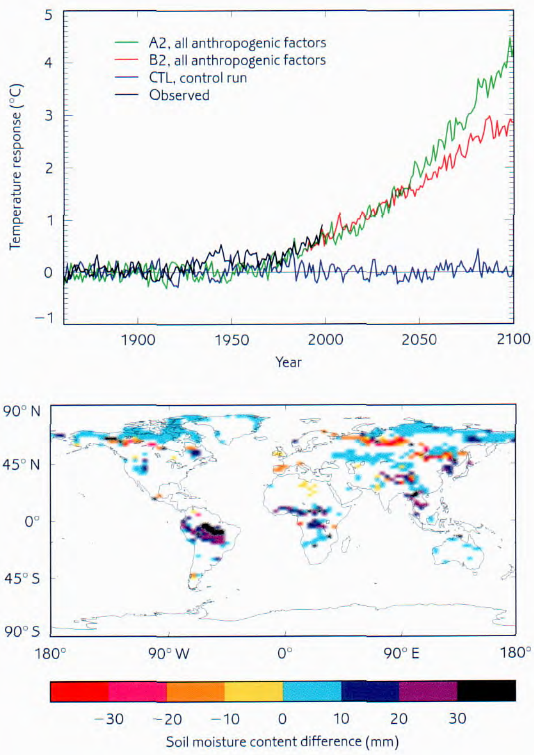


Figure 62. Top: global mean surface temperature changes due to greenhouse gas and other anthropogenic emissions in SRES scenario experiments A2 and B2, simulated by HadCM3. Also shown is CTL, a control simulation with no changes in anthropogenic emissions. Bottom: difference in annual soil moisture content (mm) in A2 compared with B2 around the 2080s (white areas show no significant difference).

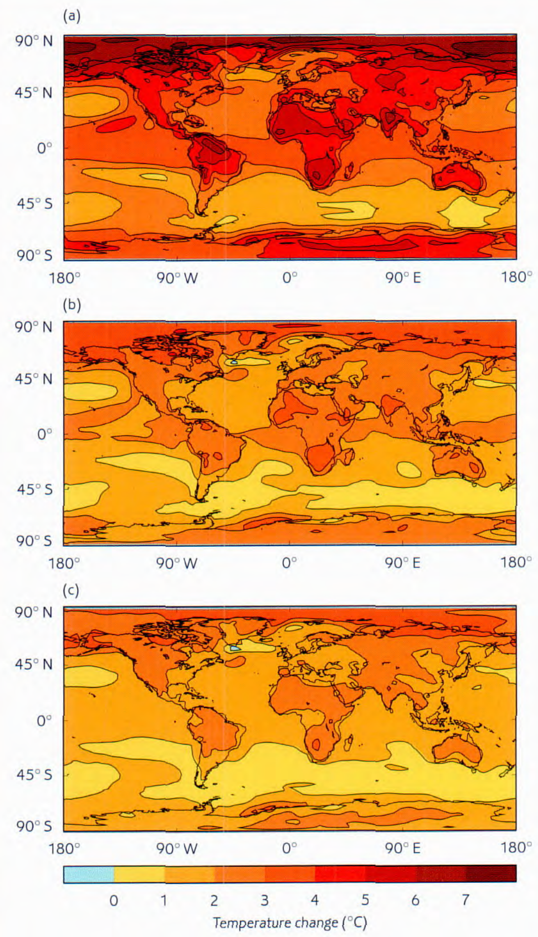


Figure 63. Annual mean surface temperature changes for 2071–2100 relative to 1961–90, simulated by HadCM2 for (a) an unmitigated emissions scenario (IS92a), and scenarios where atmospheric CO_2 concentrations stabilise at 750 ppm (b) and 550 ppm (c).

Two such scenarios were simulated using the HadCM2 model, with atmospheric CO_2 concentrations stabilising at 550 ppm and 750 ppm. When compared with a scenario in which no steps are taken to reduce future emissions, the global mean surface warming at 2100 is reduced by 40% and 55% respectively. Sea-level rise up to 2100 is also reduced. When the experiments were continued on to 2250, we found that the rate of increase of surface temperature reduces in the stabilisation scenarios. However, sea-level rise continues, with little reduction in the rate of increase due to a steady warming of the sub-surface layers of the ocean. The patterns of change in surface temperature (Fig. 63) and precipitation (not shown) are similar to the unmitigated emissions case. These results were 'fast-tracked' to impact modellers who estimated the effects of stabilisation on agriculture, natural ecosystems, water resources, coastal populations and human health. The combined climate change and impacts assessments were published as a joint brochure produced by the Hadley Centre for the UNFCCC COP5 meeting in Bonn, 1999. The results showed that stabilising the CO_2 concentration substantially delays, compared with the non-mitigation case, many of the effects of climate change expected to occur during the 21st century.

ENSO is the largest mode of interannual variability of the global climate system. ENSO events occur on an irregular three- to five-year cycle, bringing changes to the tropical Pacific climate, where the phenomenon occurs, and to many other parts of the globe via a range of remote influences. It is possible that increases in greenhouse gases may modify the ENSO cycle in the future, therefore we have examined both HadCM2 and HadCM3 for changes in the behaviour of ENSO as greenhouse gases are increased. Figure 64 shows composite ENSO events for the control experiments of HadCM2 and HadCM3, along with experiments with quadrupled CO_2 concentrations ($4 \times CO_2$). Both models have a reasonably good simulation of ENSO in their control experiments, capturing the amplitude, the irregular period of three to five years and the tendency for ENSO events to peak around the time of the northern hemisphere winter.

At $4 \times CO_2$, HadCM2 predicts a modest increase in the amplitude of ENSO events, an increase in the frequency of the cycle to a period of two to three years and a shift in the timing of events to northern autumn. However, in HadCM3, the ENSO cycle is unchanged at $4 \times CO_2$ in comparison with the control. Thus the two models show strikingly contrasting responses of ENSO to increasing greenhouse gases. The most likely cause is differences in the mean pattern of climate change between the models, caused by subtle changes between HadCM2 and HadCM3 in the representations of clouds and the atmospheric boundary layer.

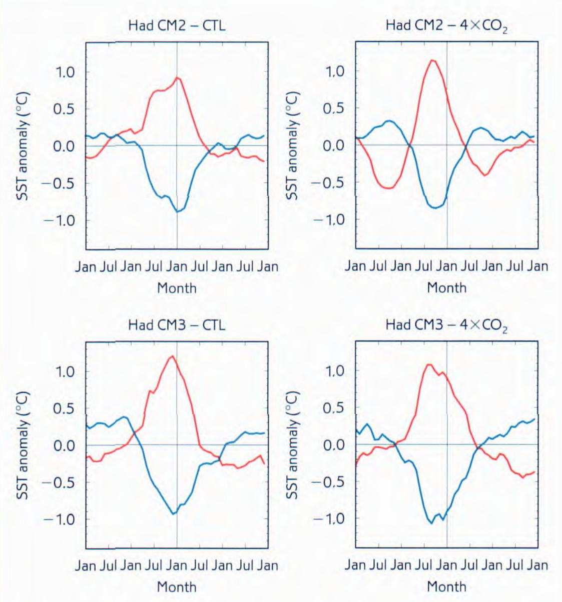


Figure 64. Composite warm (in red) and cold (in blue) ENSO events measured by NINO3 sea-surface temperatures averaged in the eastern Pacific (5° S–5° N, 150° W–90° W). Composites are formed by averaging together ENSO events that exceed one standard deviation of the NINO3 time-series. Plots are shown for the control (CTL) and $4 \times CO_2$ experiments of HadCM2 and HadCM3.

Causes of recent climate change

The rise in global average temperatures during the 20th century is very unusual compared with our estimates of ocean–atmosphere variability (e.g. the control simulation of Fig. 62). Figure 65 shows the observed temperature change near the Earth's surface. This is compared with a HadCM3 simulation that incorporates both anthropogenic and natural forcing factors likely to have influenced recent climate change. The anthropogenic factors included changes in well-mixed greenhouse gases including CO_2 and methane, changes in tropospheric and stratospheric ozone, and changes in sulphur emissions that cause changes in tropospheric aerosol and the brightness of clouds. The natural factors were changes in the amount of stratospheric dust due to explosive volcanic eruptions and changes in solar output.

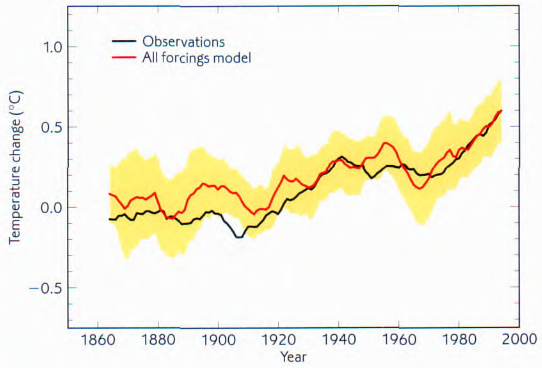


Figure 65. Ten-year averages of observed global mean surface temperature from the historical record compared against values simulated by HadCM3 when driven by observed changes in both anthropogenic and natural factors affecting the radiative forcing of climate. The yellow shading shows the level of ocean–atmosphere variability that can occur in HadCM3 in the absence of changes in forcing — the observations should lie within this region on 90% of occasions if the model is successfully capturing the observed changes.

The simulation reproduces the main features of the temperature record since 1860, with warming in the early part of the 20th century followed by a levelling off in temperatures prior to renewed warming over the past 30 years. We have also made an ensemble of four HadCM3 simulations in which only anthropogenic changes are included, and another ensemble in which only natural changes are represented. Advanced statistical techniques, which take into account both the temporal and spatial variations of the model response, show that neither ensemble is consistent with the observed record. The natural ensemble over the past 30 years cools rather than warms, and the anthropogenic ensemble does not capture the warming observed in the first half of the 20th century. Only by including both natural and anthropogenic forcings is it possible to explain the observed temperature record.

Atmospheric dispersion

Understanding and predicting the processes by which airborne pollutants are transported in the atmosphere is important in a wide variety of problems. These range from predicting the spread of material from major atmospheric releases, such as from nuclear accidents, chemical spills or volcanic eruptions, to forecasting and understanding air quality and atmospheric chemistry. We maintain and develop a number of models for predicting and understanding dispersion. In particular, the Nuclear Accident Model (NAME) particle model is used for predicting transport over 10–1,000 km, and the Atmospheric Dispersion Modelling System (ADMS) model (developed in collaboration with Cambridge Environmental Research Consultants Ltd and the University of Surrey) is used for shorter ranges.

The NAME model

Over the past year, both the deposition and advection schemes in the NAME model have been improved. For example, the model has been adapted to use high-resolution precipitation fields from Nimrod, resulting in significantly improved estimates of the deposition of pollutants to the ground by rain.

NAME has also been developed to predict the spread of ash plumes from volcanic eruptions by including a sedimentation scheme to represent the fall of ash particles under gravity. We are now responsible for generating volcanic ash warnings for aviation in the North Atlantic.

Air quality

The NAME model continues to be developed for forecasting and understanding air quality. Routine forecasts of NO_x and SO_2 are now routinely generated from NAME, and these forecasts will shortly replace those currently generated operationally by the simpler BOXURB model.

The fine fraction of airborne particulate matter (PM10) is a matter of growing concern with respect to human health. NAME has been used to study the transport of both primary particulates and sulphate aerosol, a major component of secondary PM10. Figure 66 shows modelled versus measured PM10 for August 1997 in London, with the relative contribution from primary and secondary particulates shown. The model clearly reproduces the main characteristics, although it is not achieving the magnitude observed. A further study is under way to investigate this.

NAME is also used to analyse pollution episodes. For example, high levels of SO_2 were observed in Nottingham and Birmingham on 2 September 1998. The episode generated many calls to the Environment Agency from members of the public concerned about air quality. The timing of the peaks measured at both Nottingham and Birmingham were captured well by the model (Fig. 67), although the magnitude of the Nottingham peaks was slightly under-predicted. This under-prediction is thought to be a result of an anomalously low boundary-layer height that was not captured by the mesoscale version of the UM. The model was also used to identify the most likely sources and their relative contribution to SO_2 levels.

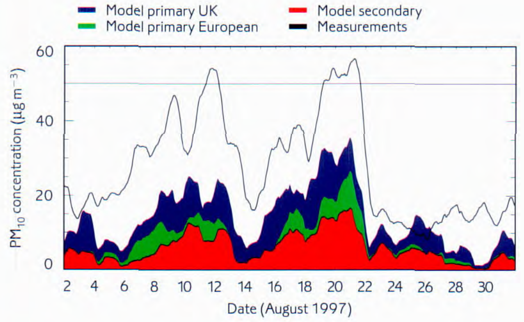


Figure 66. NAME model predicted and observed PM10 in London in August 1997. Red indicates sulphate aerosol, blue indicates primary UK PM10, green indicates primary European PM10. A running 24-hour average has been applied to both sets of data.

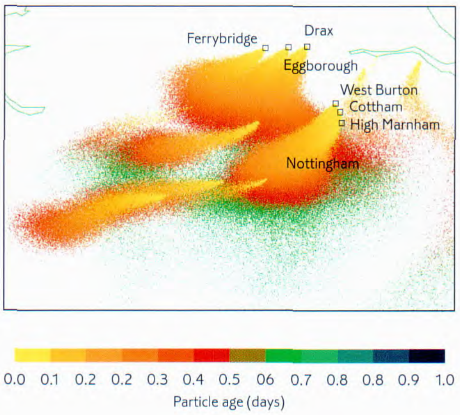


Figure 67. Predicted SO_2 plume in the Nottingham/Birmingham area at 1600 UTC on 2 September 1998.

Short-range dispersion

Short-duration fluctuations in the concentration of pollutants are important in assessing hazards from toxic, flammable, odorous or obscurant materials, and even for some substances that are routinely emitted, such as SO_2, where short periods of high concentrations can cause problems in asthma sufferers. In conjunction with the Defence Evaluation and Research Agency, we have conducted a programme of research into such fluctuations over several years. Over the past year work has focused on the development of models to simulate the fluctuating concentration time-series, building on previous work predicting the statistics of such time-series. The simulation results will form an input to risk assessment models in order to determine the effect of fluctuations on toxicity and to assess the effectiveness of strategies for detecting hazardous substances. Figure 68 shows a comparison of real and simulated time-series. Initial results are encouraging, suggesting this will prove a valuable technique when refined further.

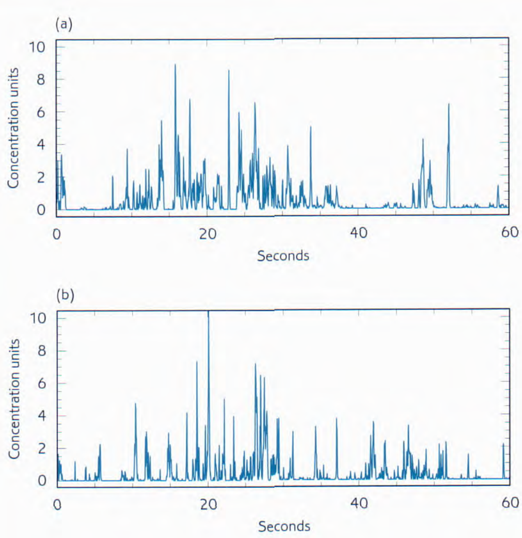


Figure 68. (a) Typical observed time-series of concentration, and (b) simulated time-series.

Urban meteorology

In developing urban air-quality models, it has become clear that there are limitations in our understanding of the urban boundary layer. In collaboration with Met. Research Unit (MRU), Cardington, a series of measurement campaigns has been undertaken in Birmingham.

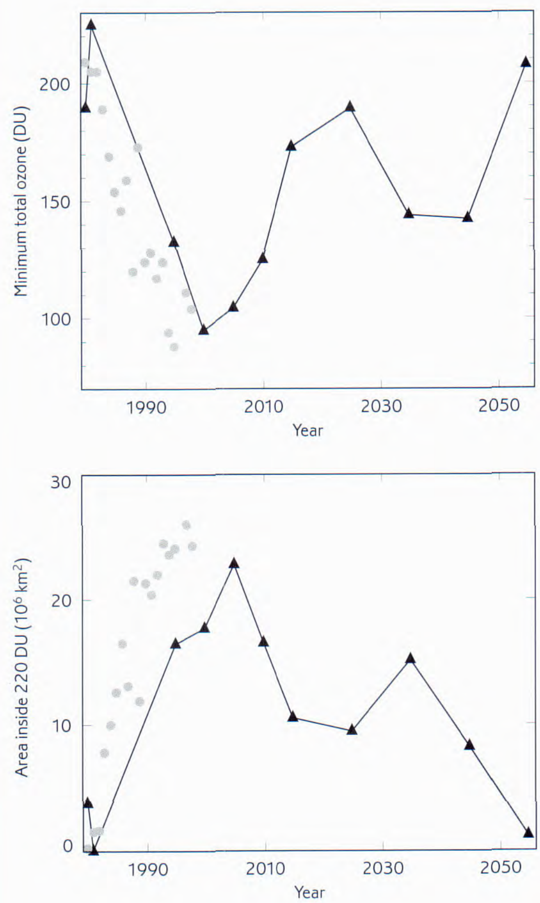


Figure 69. Upper panel: minimum total ozone over Antarctica in one-year simulations of the coupled chemistry-climate model (shown as triangles). Observations for the period 1980–97 are indicated by circles. Lower panel: maximum area inside the 220 Dobson Units (DU) total ozone contours for model results (shown as triangles) and observations (shown as circles).

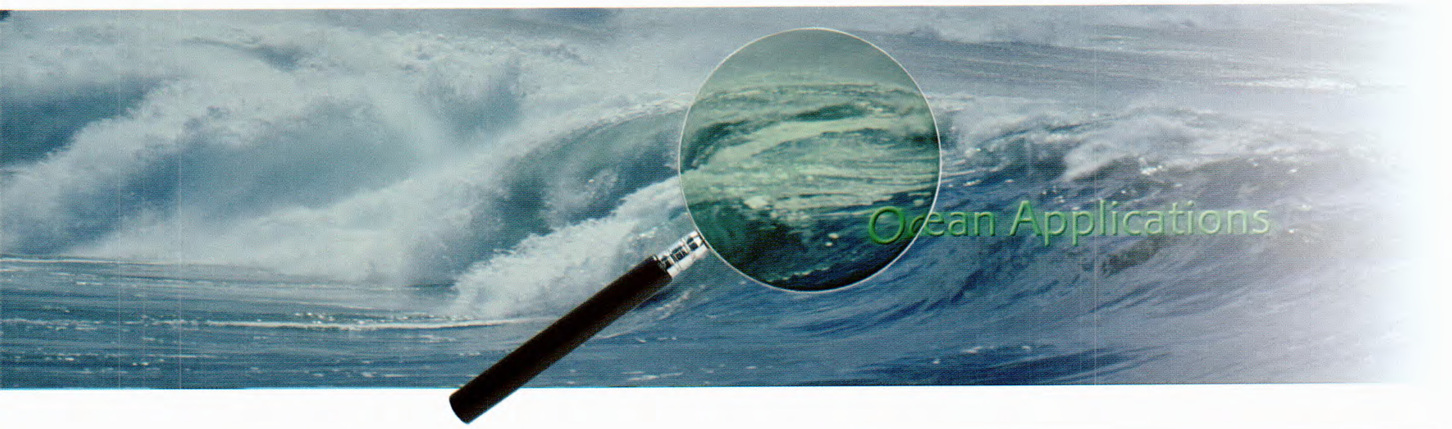
Observations are being compared with surface energy balance models to produce an improved understanding of the urban boundary layer.

Stratospheric processes research

The impact of atmospheric dynamics on future ozone behaviour remains an important theme, and has been explored in a sequence of simulations using the UM. The influence of the quasi-biennial oscillation in the UM (see **Simulating the QBO** in **Numerical Weather Prediction**) on ozone has been investigated. However, so far the results have been rather variable due to the extreme sensitivity of lower stratospheric ozone to the model temperatures.

Another important issue has been the impact of increasing greenhouse gases on stratospheric circulation and climate. The increase in mean tropical ascent in the lower stratosphere determined from a 60-year simulation of the UM of approximately 0.5% per annum, although small, could have important implications for the transport of chemicals, such as water vapour, into the stratosphere.

The coupling between stratospheric climate change and ozone change was reported in last year's *Scientific and Technical Review*. Figure 69 shows recent predictions for the future depth and size of the Antarctic ozone hole. While it is expected to disappear by about the year 2050, these results suggest that the weakening of the ozone hole, due to the reduction in atmospheric chlorine and bromine amounts, will not be steady. This arises from the increases in greenhouse gases that cool the lower stratosphere and reduce ozone because of the complex interactions between the processes present.



Ocean Applications

Ocean Applications develops, and brings to implementation, the ocean modelling systems required to meet Met. Office customer needs. This includes operational ocean models for short-period (to five days ahead) forecasting, together with the application of ocean models for seasonal prediction and climate research. For the latter, we provide the ocean component of the Hadley Centre's coupled ocean–atmosphere models.

Operational ocean modelling

Forecasting–Ocean Atmosphere Model (FOAM)

FOAM, which has global coverage at 1° resolution, is run operationally, daily, to provide forecasts to five days ahead for ocean temperature, salinity, currents and sea-ice cover. Higher-resolution, limited-area models, nested within the global FOAM, are being developed to forecast the ocean on the mesoscale and to provide boundary conditions for shelf-seas models. A ⅓° (33 km) resolution model covering the Atlantic and Arctic is planned to be ready for operational implementation in 2001. We have also developed a ⅑° (11 km) resolution model of the Caribbean and Gulf of Mexico nested within the Atlantic model.

Figure 70 illustrates surface currents from the three model configurations for the Gulf of Mexico. The global model is unable to represent the loop current at all. The 33 km resolution model represents it, but does not simulate the shedding of eddies as well as the 11 km resolution model does.

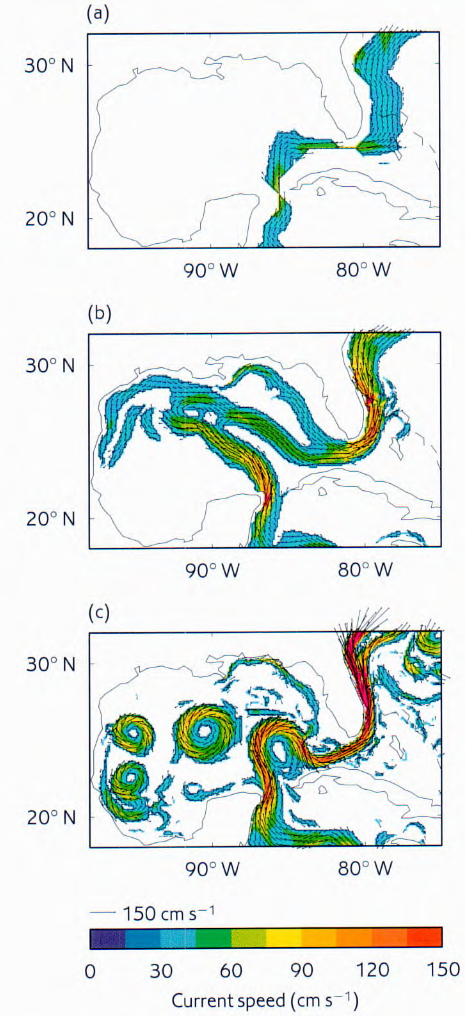


Figure 70. Surface velocities in Gulf of Mexico on 15 July 1998 from (a) 1° global model, (b) 33 km Atlantic model and (c) 11 km Gulf of Mexico and Caribbean model.

Two satellites currently carry altimeters. They measure the height of the sea surface to a root-mean-square accuracy of 3 cm, and deliver the data within two days of the measurement. These data have been assimilated into the models, where the assimilation procedure has been optimised to use statistics consistent with the differences between the measurements and the models. Figure 71 shows that the surface height field in the high-resolution model with altimeter assimilation better matches that from a statistical analysis of the measurements, and is a significant improvement over the analysis without altimeter assimilation.

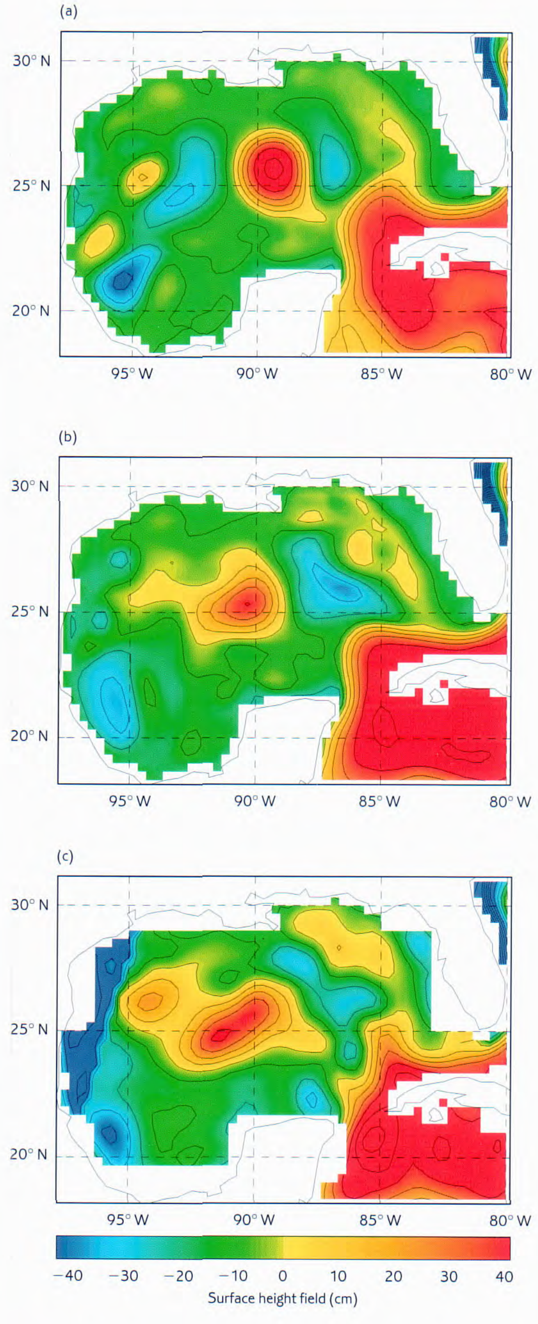


Figure 71. Surface height fields for 15 July 1998, (a) without altimeter assimilation, (b) with altimeter assimilation, and (c) gridded altimeter data from CLS, France.

Shelf-seas modelling

To predict the synoptic-scale evolution of temperature, salinity and current profiles over the continental shelf and at the shelf break, a baroclinic model is run for north-west European continental shelf seas. The model has been developed by the Centre for Coastal and Marine Sciences, Proudman Oceanographic Laboratory. At the sea surface, heat and momentum forcing is provided by The Met. Office's global NWP model, and at the deep ocean boundaries tidal constituents, and climatological values for temperature and salinity are specified.

Comparison of modelled and observed daily averaged sea-surface temperature (SST) from March 1998 to March 1999, and also for Summer 1999, shows good agreement in the North Sea (Fig. 72). The time-series show how the shelf-seas model followed the warming and cooling during July and August 1999. The figure also shows the modelled seabed temperature, indicating a drop in temperature in July when a seabed front passed over. Similar behaviour was also seen in the model during 1998.

Figure 72. Time-series of modelled and observed temperature at 57° N, 0° E between March and November 1999. Observed daily averaged SST from a moored buoy is shown in blue, modelled SST in solid red, and modelled seabed temperature in dashed red.

Figure 73 shows a model cross-section of temperature, south to north along the 0° meridian on 1 August 1999. This indicates a cold pool of bottom water and strong surface stratification. During a cooler period in late July, the vertical gradient of temperature in the surface layer was much weaker.

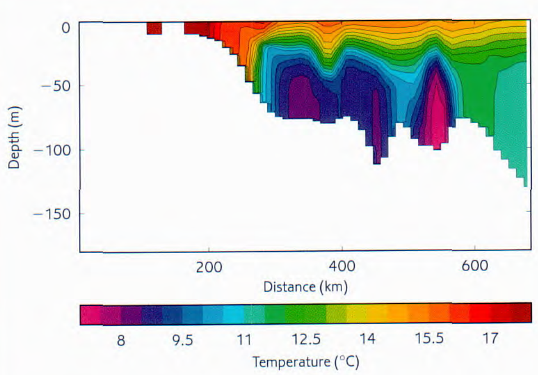


Figure 73. Cross-section of modelled temperature (°C), from 52° N to 58° N along the 0° meridian on 1 August 1999.

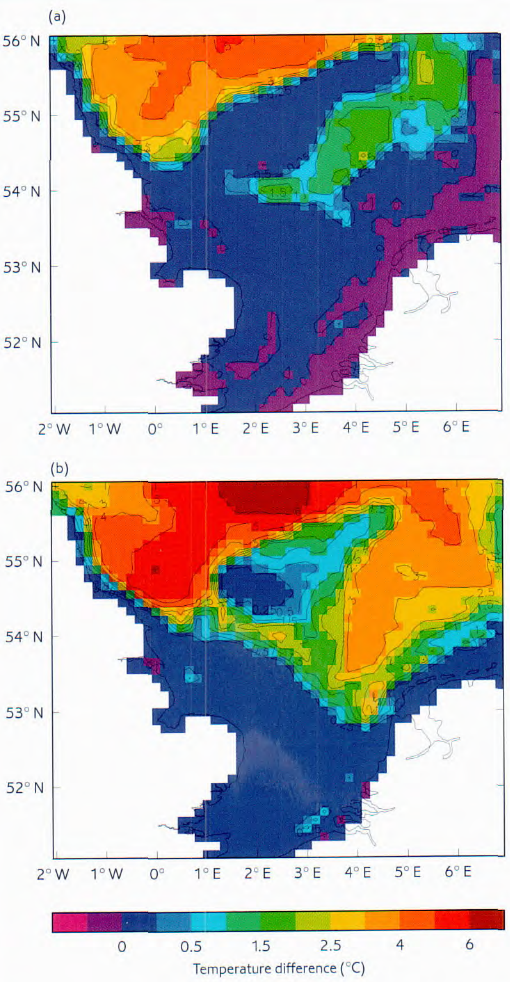


Figure 74. Modelled surface to seabed temperature difference (°C) on 29 August, showing the position and strength of the North Sea tidal mixing fronts for (a) 1998 and (b) 1999.

The North Sea has a seasonal cycle, with stratification developing in early spring, and tidal mixing fronts separating the shallower well-mixed water from the deeper stratified water. Figure 74 compares the surface and seabed temperature difference over the North Sea for 29 August in 1998 and 1999. This illustrates how the strength and position of the tidal mixing front can vary depending on the meteorological conditions from one year to next.

Wave modelling

The wave model has been extended to include interactions between waves and time-varying currents. The new model has been set up on the same grid (~12 km resolution) as the operational storm-surge model, and run in a pre-operational trial using surface winds from mesoscale NWP, and current speed and direction from the surge model.

Model results show that the maximum impact of tidal currents on the waves occurs some three hours after the time of the strongest currents, i.e. when the current speeds are changing most rapidly. For waves of up to 2–3 m height, the wave height can be affected by up to 10%.

Figure 75(a) shows the significant wave height from the UK waters wave model for the Christmas Eve storm, at 00 UTC on 25 December 1999. High waves to the south-west are evident, extending eastward into the English Channel. The effect of including wave–current interactions on significant wave height is shown in Fig. 75(b), and has been to reduce wave heights in the English Channel by over 30 cm because of a wind-driven surge current flowing in the same direction as the waves.

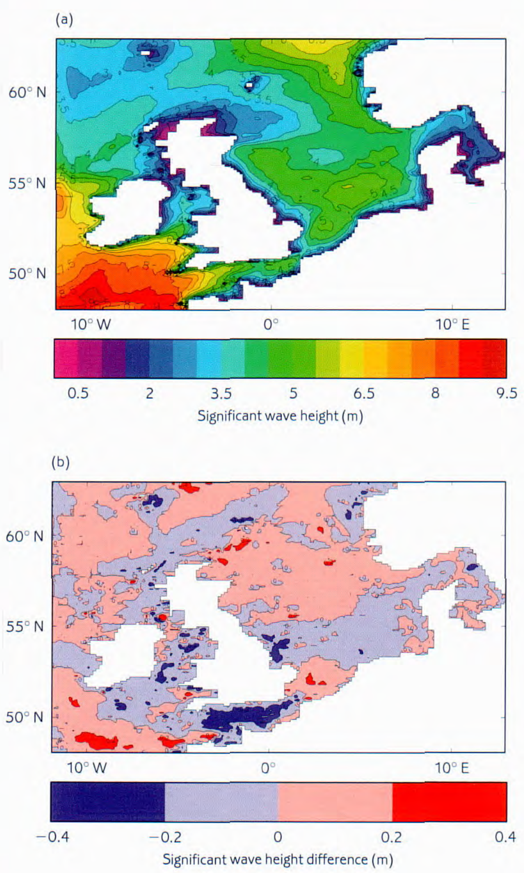


Figure 75. (a) Significant wave height (m) from the UK waters wave model, including the effect of currents on the waves. (b) The difference in significant wave height (m) from including wave–current interactions. Examples are for 00 UTC on 25 December 1999.

Seasonal modelling and prediction

Research and development on seasonal forecasting models are carried out using dynamical physically based models together with statistical relationships based on historical data. The main source of predictive skill is SST, which changes relatively slowly and can itself be predicted on a seasonal timescale.

Coupled models

The main dynamical prediction tool is a coupled general circulation model, suitable for making large-scale forecasts several months ahead by taking into account interactive changes in the oceans and atmosphere. This model has been used to monitor the continuation of the La Niña episode (cooler-than-normal tropical Pacific sea-surface temperatures) through 1999.

The initial upper-ocean state is an important component of any coupled prediction system. As part of the partially European Commission-supported DUACS (Developing Use of Altimetry for Climate Studies) project, a series of ocean analyses extending over the past seven years has been produced to investigate the impact of various sources of ocean observations. The results have demonstrated that sea-level data (inferred from satellite altimetry) can be used to improve the upper-ocean state for prediction purposes.

Statistical predictions

Statistical methods were used to generate seasonal predictions for selected regions in Europe, Africa and South America. Probability forecasts of European Summer 1999 temperature and rainfall were published on The Met. Office web site in March (Fig. 76) and updated in July. Both forecasts indicated highest probabilities for above-normal temperature and below-normal rainfall.

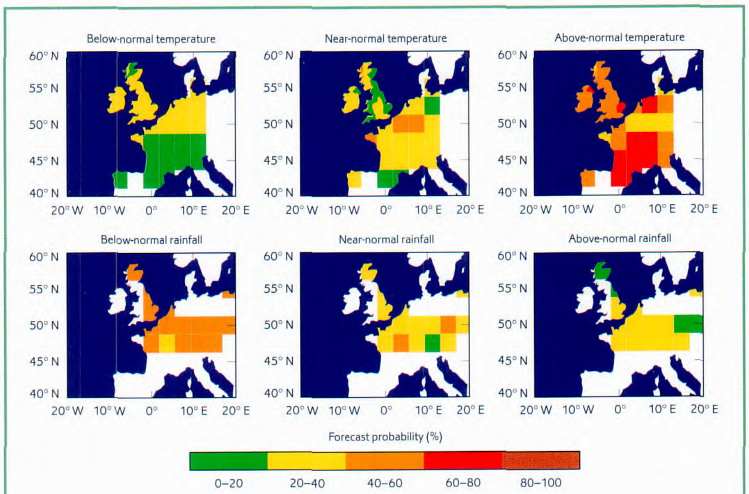


Figure 76. The European forecast of temperature and rainfall for July–August 1999, issued in March 1999. This statistical forecast uses a North Atlantic SST pattern as a predictor.

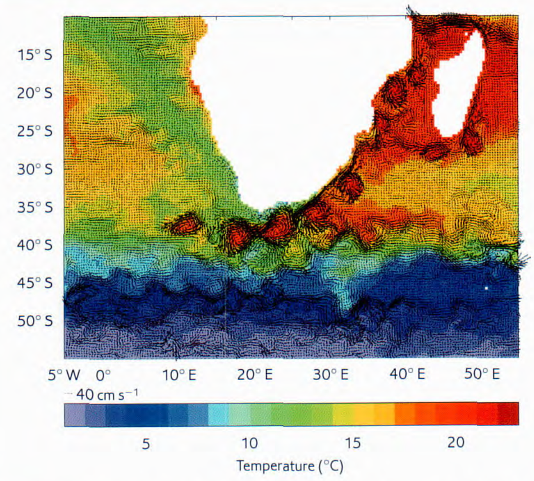


Figure 77. Simulated temperature (°C) and currents at 140 m in the ⅓° global ocean model. The figure shows the shedding of eddies in the Agulhas current region (off South Africa).

These conditions were indeed widespread in western Europe during Summer 1999.

Innovative forecast activities in 1999 included a global temperature forecast for the year 2000 (in collaboration with Climate Research Division) and contributions to the millennium forecast (produced with Numerical Weather Prediction Division in September 1999) of likely conditions in the UK for the end of 1999.

Ocean modelling for climate studies

Ocean and sea-ice model development

Development of the ⅓°resolution global ocean model, which will be coupled to the standard atmosphere and ice models, is near completion. The model is significantly more efficient than earlier versions, and remains stable for decade-length integrations. An example of the features simulated at this resolution is shown in Fig. 77, illustrating eddies being shed in the Agulhas region at the southern tip of Africa. These eddies are thought to make an important contribution to the ocean heat and salt transports.

In addition, a variety of improvements have been made to both the parametrization of horizontal and vertical mixing in the model.

To accurately simulate the motion of sea ice, and the build-up of ice in Arctic regions, the effects of the resistance of ice to compression and shear are being incorporated into the model. The current climate model has a very simplistic representation of this, and the motion and build-up of ice are not well simulated.

Ocean-model validation

The Hadley Centre coupled climate model (HadCM3) successfully simulates many features of the North Atlantic Oscillation (NAO) and shows significant variability at decadal timescales. It has recently been discovered that anomalies in SST propagate across the Atlantic from Florida towards Iceland in approximately eight years. Similar anomalies have been found in the model integrations, and work has been done to understand the mechanism of these propagating anomalies. Strong decadal signals are also found in the Gulf Stream transport, both in the data and the model, and these are under investigation.

The freshwater cycle, particularly in the North Atlantic, is important for the vertical overturning of the oceans, the thermohaline circulation (THC). It therefore needs to be well simulated by the coupled model. The model's freshwater budget has been analysed and validated against observations. Using the results of this validation, the sensitivity of the model climate to changing aspects of the freshwater cycle is being investigated.

The ocean and climate change

Recent observations show relatively large changes in temperature and salinity of intermediate waters on decadal timescales. An experiment with anthropogenic forcing shows a freshening of the intermediate waters in the Indian Ocean (Fig. 78) which is comparable with the observed freshening. Water masses are identified by their potential density, and a large freshening can be seen in the density range 25.5–26.0, corresponding to the so-called 'subantarctic mode water' (SAMW). SAMW is formed at the surface in the Indian Ocean, and occupies a range of depths around 300–400 m at the latitude shown here. These results suggest that the SAMW may be a particularly sensitive indicator of anthropogenic climate change and should be measured as part of a climate-monitoring system.

In climate-change simulations there is a reduction in the strength of the North Atlantic THC. To investigate the effects of a potential collapse in the THC, the THC was shut off in an idealised experiment by applying a freshwater pulse in the North Atlantic. It was found that the resulting change in surface air temperature is global and has a marked north–south pattern (Fig. 79). Most of the northern hemisphere experiences cooling within two decades after the initial pulse, with a maximum of over 5 °C in the North Atlantic. This experiment highlights the strong link between the THC and global climate and emphasises the importance of an accurate representation of the THC in models.

The ocean carbon cycle

The Hadley Centre Ocean Carbon Cycle Model (HadOCC) simulates the movement of carbon around the ocean system, including exchange of carbon dioxide (CO_2) with the

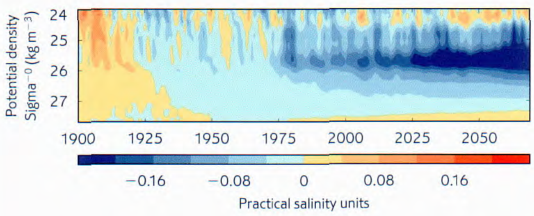


Figure 78. Zonally averaged salinity anomaly at 32° S in the Indian Ocean in a climate change experiment with imposed anthropogenic forcing. The anomalies have been calculated on potential density surfaces.

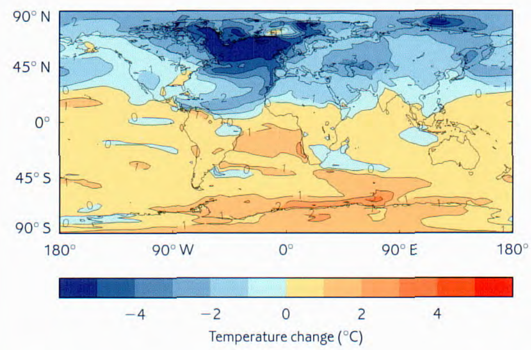


Figure 79. The decadal mean air temperature change (°C) for years 21–30 in a coupled HadCM3 experiment in which the Atlantic thermohaline circulation has been artificially suppressed.

atmosphere and the cycling of carbon by marine plankton. To examine the possible feedback of the carbon cycle on climate, simulations have been completed with HadOCC coupled to an atmosphere model with freely evolving CO_2 and a model of the terrestrial biosphere. The model shows the ocean taking up CO_2 from anthropogenic emissions in the future at a steady rate (Fig. 80).

These experiments used the coarse-resolution (2.75° × 3.75°) ocean model. The representation of ocean physics has been shown to be greatly improved by moving to 1.25° resolution and this also has positive benefits for aspects of ocean carbon cycle simulations.

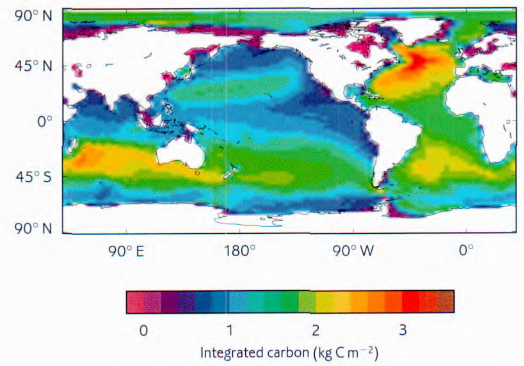
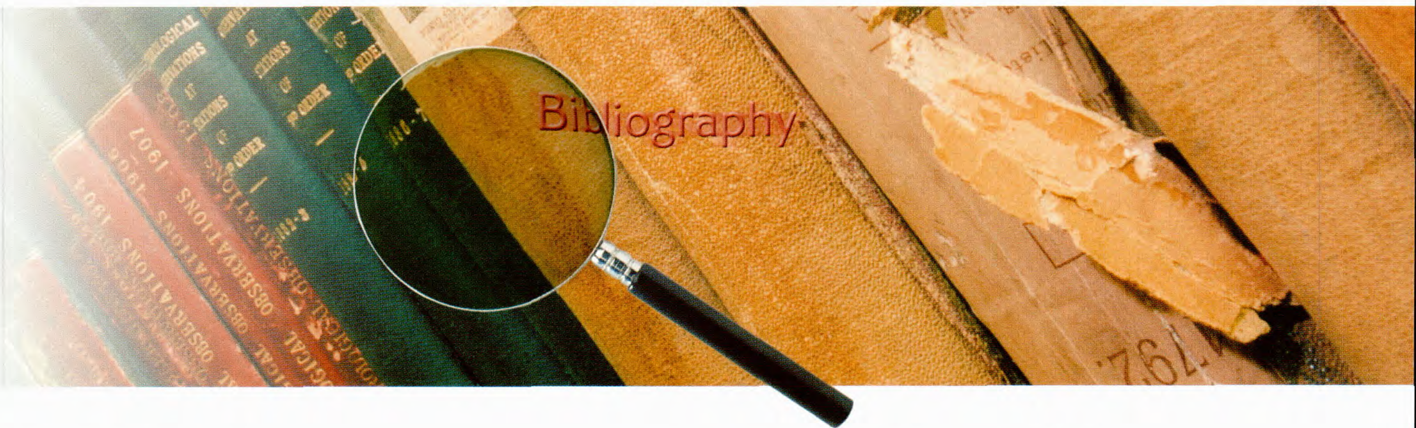


Figure 80. Simulated distribution of depth-integrated carbon (kg C m^{-2}) in the ocean from anthropogenic CO_2 emissions for the decade 2081–90. The figure illustrates the fate of anthropogenic CO_2 emissions in the oceans.



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Acronyms

3DVAR	Three-dimensional variational analysis
AMDAR	Aircraft Meteorological Data and Reporting
AMSU	Advanced Microwave Sounding Unit
ARIES	Airborne Research Interferometer Evaluation System
ASAP	Automated Shipboard Aerological Programme
ASDAR	Aircraft to Satellite Data Relay
ATOVS	Advanced TIROS Operational Vertical Sounder
CAPE	Convective Available Potential Energy
CMETS	Computerised Meteorological System
CRM	Cloud-resolving model
DUACS	Developing Use of Altimetry for Climate Studies
ECMWF	European Centre for Medium-range Weather Forecasts
ENSO	El Niño Southern Oscillation
EUCOS	EUMETNET Composite Observing System
EUMETNET	Advanced TIROS Operational Vertical Sounder
EWP	England and Wales Precipitation
FASTEX	Fronts and Atlantic Storm Track Experiment
FCCC	Framework Convention on Climate Change
FOAM	Forecasting Ocean–Atmosphere Model
FSSSI	Forecasting for Specific Sites: System Implementation
GANDOLF	Generating Advanced Nowcasts for Deployment in Operational Land-based flood Forecasts
GPS	Global Positioning System
GPCS	General Purpose Computing Service
GTS	Global Telecommunication System
IASI	Infrared Atmospheric Sounding Interferometer
ICAO	International Civil Aviation Organization
INTACC	Interaction of Aerosol and Cold Clouds
IPCC	Intergovernmental Panel on Climate Change
IWC	Ice water content
JCMM	Joint Centre for Mesoscale Meteorology
LEO	Low Earth-orbiting satellites
LES	Large-eddy simulations
MAP	Mesoscale Alpine Programme
MARSS	Microwave Airborne Radiometer Scanning System
METOP	Meteorological Operations Satellite
MIDAS	Met. Office Integrated Data Archive System
MIST	Meteorological Information Self-briefing Terminal
MOMIDS	Met. Office Military Information Distribution
MONET	Met. Office Noise Evaluation Tool
MORSN	Met. Office Remote Sites Network
MOS	Model Output Statistics
MOTH	Measurement of Tropospheric Humidity
MRF	Met. Research Flight
MSU	Microwave Sounding Unit
NAME	Nuclear Accident Model
NAMIS	Nato Automated Meteorological Information System
NAO	North Atlantic Oscillation
NATS	National Air Traffic Services
NMC	National Meteorological Centre
NWP	Numerical weather prediction
PYREX	Pyrenees mountain experiment
RMDCN	Regional Meteorological Data Communications Network
SOP	Special Observing Period
SSFM	Site-Specific Forecast Model
SSMI	Special Sensor Microwave Imager
SST	Sea-surface temperature
STAAARTE	Scientific Training and Access to Aircraft for Atmospheric Research Throughout Europe
TAF	Terminal Aerodrome Forecast
TGCIA	Task Group on Climate scenarios for Impact Assessment
THC	Thermohaline circulation
TIROS	Television Infrared Observation Satellite
TMD	Thailand Meteorological Department
UM	Unified Model
UMIST	University of Manchester Institute of Science and Technology
UNFCCC	United Nations Framework Convention on Climate Change
WAFS	World Area Forecast System
WAFTAGE	Winds Analysed and Forecast for Tactical Aircraft Guidance over Europe
WWRP	World Weather Research Programme

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